Proceedings World Geothermal Congress 2026
Calgary, Canada, June 8 – 11, 2026

Techno-economic Optimization of Geothermal Systems with TANGO

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Keywords: Techno-Economic Analysis, Optimization, CPG, LCOE, EGS, AGS

ABSTRACT

Geothermal energy is a key pillar of the global energy transition due to its reliability, low carbon footprint, and ability to provide baseload power. However, its widespread adoption is often constrained by a relatively high Levelized Cost of Energy (LCOE), driven by factors such as high upfront investment and complex subsurface conditions. Optimization of operational parameters offers a practical approach to improving economic performance and making geothermal systems more competitive. In this context, we present TANGO (Techno-economic ANalysis of Geo-energy Operations), a Python-based tool developed for the design, assessment, and optimization of geo-energy systems. TANGO integrates geothermal modeling with techno-economic analysis to evaluate and improve system performance across a range of operating scenarios. By optimizing parameters such as mass flow rate, reinjection temperature, and surface plant specifications, TANGO identifies configurations that minimize LCOE while maintaining technical feasibility. Through representative case studies, we demonstrate how TANGO effectively supports decision-making by highlighting economically optimal strategies tailored to site-specific conditions. The results underscore the tool's capability to reduce costs and enhance the viability of geothermal projects, thereby reinforcing the critical role of geothermal energy in achieving a sustainable and resilient energy future. Abstract should be one paragraph only

1 INTRODUCTION

Geothermal energy promises to be a critical component in the global transition towards sustainable, renewable, and low-carbon energy systems, driven by its reliability, low environmental footprint, and resource abundance. Whereas intermittent renewable sources such as solar and wind provide power at particular and sometimes unreliable times of the day, geothermal energy can provide a continuous and stable power output, a critical feature for grid stability and baseload power. Furthermore, the distributed nature of geothermal energy systems makes it an attractive source of local power generation and energy security for countries reliant on energy imports. Direct use of geothermal power for district heating and industrial applications makes the most efficient use of the resource, supplying heat directly to consumers.

The geothermal industry faces considerable economic challenges, due to the capital-intensive nature of drilling and exploration of the subsurface, as well as the uncertainty and financial risks involved in developing geologically complex reservoirs. Whereas other renewable energy sources, such as solar and wind, have lowered costs through technological advancements and economies of scale, geothermal power remains prohibitively expensive or uncertain in many places, hindering widespread adoption and limiting investment interest. Innovative technological solutions, policy support, and financial incentives are needed to make geothermal energy competitive in renewable energy portfolios.

Reservoir modeling has long been used to characterize geothermal reservoirs and predict well flow rates and temperatures. These simulation tools address the physical and geologic problems at hand, allowing for the optimization of the design and management of geothermal systems while forecasting long-term resource utilization and environmental impacts. Alone, these models do not account for economic constraints which ultimately decide the fate of the underlying asset.

Techno-economic analysis combines the simulation of the physical world with models of financial constraints and goals, using reservoir models to optimize the economic output of a geothermal system. Examples of such tools include the Geothermal Electricity Technology Evaluation Model (GETEM) (Mines, 2016), GEOthermal energy for Production of Heat and electricity ("IR") Economically Simulated (GEOPHIRES) (Beckers and McCabe, 2019), and Flexible Geothermal Economics Modeling (FGEM) (Aljubran and Horne, 2024). These software packages can provide valuable analysis for specific applications, but suffer from a lack of flexibility and

transparency, often relying on unpublished simulation results or models which assume single-phase aqueous flow conditions. This makes modeling innovative power plant designs and concepts difficult, such as advanced geothermal systems (AGS) (Malek, et al., 2022) and CO_2 Plume Geothermal (CPG) (Randolph and Saar, 2011).

We introduce TANGO (Techno-economic Analysis of Geo-energy Operations) – a cutting-edge simulation tool offering fast and flexible modeling of the full cycle of reservoir, surface facilities, and economics of geothermal operations. TANGO uses a modular framework to couple reservoir simulations, wellbore models, fluid flow and energy conversion through pipelines and power plants, and economic models for all the costs thereof into a single workflow, enabling operators to accurately assess - and optimize - the financial viability of their operations. The modularity of TANGO allows for users to substitute native models with their own by integrating with commercial simulators or user-defined models. TANGO also accounts for the various cost components of geothermal operations, such as permitting, exploration, stimulation, and surface plant costs and maintenance. An intuitive graphical user interface allows users to customize models and system configurations.

Basic, modifiable examples of the TANGO software are available at TANGO.app. This webapp showcases a select set of use cases with the TANGO-native models for reservoir, wellbore, surface, and economics. Advanced features, such as 3rd party model interfaces and optimization workflows, are not available online as of writing.

By equipping researchers and industry professionals in the geothermal energy community with a power, adaptable, and high-fidelity techno-economic assessment tool, we hope to accelerate geothermal development and productivity.

2 TANGO OVERVIEW

Development of the TANGO Python codebase originated in 2023 at the Geothermal Energy and Geofluids (GEG) group at ETH Zurich. TANGO was initially developed for simulating geothermal systems. The codebase is designed to be flexible and adaptive for supporting a variety of geothermal system types with different settings for both surface and subsurface models. Its capabilities have later been extended to encompass other geo-energy systems.

2.1 Simulation workflow

For a comprehensive understanding of the TANGO architecture and a step-by-step simulation workflow, a detailed overview is provided below:

2.1.1 Reading input file(s)

The input file (YAML) consists of several sections, each of which entails several keywords, as shown in Table 1, and these will be elaborated in the following sections. The input overview and an example are shown in Table 1. Before proceeding to the core execution of TANGO, input data validation is performed to ensure the presence of all the required inputs and prevent the use of unrealistic settings. For optional input parameters, TANGO defaults to reasonable values when not provided in the input file.

Table 1: Input file description.

Section	Description
RUNSPEC	Run title, workflow specifications
GRAPH	Computing unit specifications and their connections
PROPS	Fluid and rock properties
COMPUTING UNIT	Parameters for computing units defined in GRAPH section
SCHEDULE	Parameters and controls for wells and time stepping
ECONOMIC	Economic parameters

2.1.2 Physical system construction

This step involves constructing and initializing the numerical geo-energy system using the GRAPH section of the input file. The geo-energy system is conceptualized as a graph, where discrete components of the system (e.g., a surface facility, wells, and a reservoir) described by computing units correspond to nodes, and the connections between these units/nodes correspond to edges. The use of a graph structure facilitates flexible design considerations for various types of geo-energy systems. Figure 1 provides an illustrative example of a graph representing a doublet geothermal system, featuring green circles as computing units, and purple and blue boxes representing inputs and outputs, respectively. The key concept in this framework is the 'computing unit', serving as a wrapper encapsulating a specific model. It offers the flexibility to encapsulate various model options, including native built-in models, user-defined custom Python codes, or external simulators. Further insight into the operations within a computing unit is provided in the following section. Moreover, TANGO utilizes the JSON format as a standardized data type to facilitate seamless communication across computing units (green arrows in Figure 1). This is particularly beneficial when different units employ diverse models with specific input/output formats.

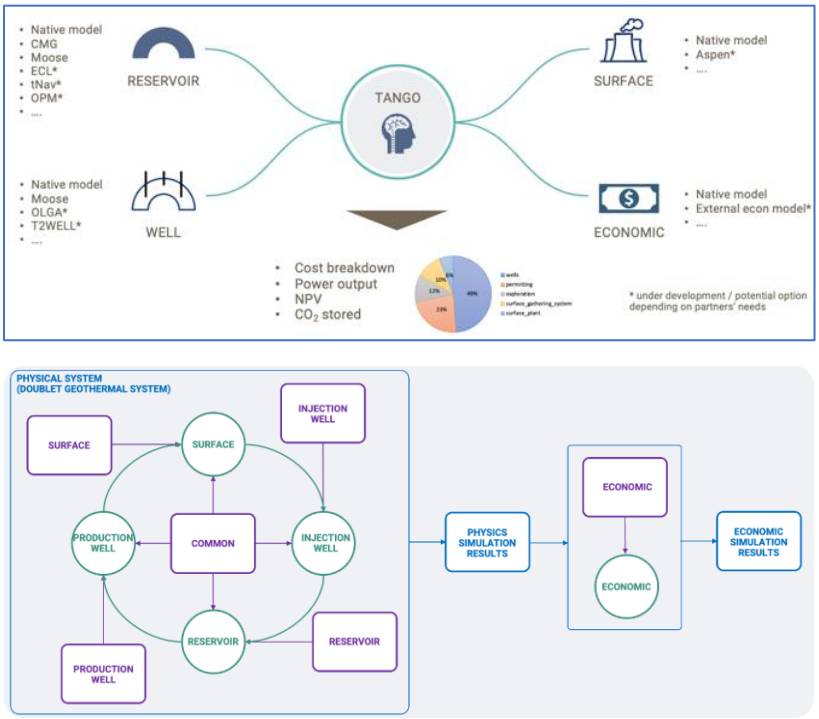


Figure 1: Graph-based representation of a doublet geothermal system

2.1.3 Simulation (physical system)

The simulation for the physical system entails a process akin to graph traversal, where the physical system is abstracted as a graph, and each computing unit (node) is systematically visited and updated. Each visit to a node entails the following steps:

1. Pre-processing: A JSON object from the source computing unit and the static inputs (purple boxes in Figure 1) to generate an input file or object compatible with the model in use.
2. Model execution: The model is executed using the input file or object generated in the pre-processing step, and its states are updated.
3. Post-processing: Model-specific outputs, such as simulator-specific output files or Python objects, are processed to generate a JSON object, which will subsequently be passed on to the next computing unit.

These steps above are iteratively executed for all computing units at each time step, following the settings for time stepping specified in the SCHEDULE section.

2.1.4 Economic Evaluation

After completion of the simulation of the physical system, the economic evaluation commences by computing the costs associated with both the construction and operation of the physical system, such as CAPEX (e.g., drilling costs, equipment costs for the surface facility, etc.), and OPEX. To this end, we leverage the get_cost method implemented in each computing unit to assemble the costs associated with each of the units, such as drilling cost, cost to build a power plant, etc. Subsequently, techno-economic metrics, including the levelized cost of electricity (LCOE) and net present value (NPV), are computed using the simulation results obtained from the physical system.

2.2 Model details

TANGO features "native" simulations capabilities for reservoir, wellbore, surface, and economic modeling that run quickly with simplifying assumptions (Adams et al., 2021). As such, they are primarily intended to be used for preliminary assessment or screening of geo-energy systems. For more detailed studies, users can employ higher fidelity external simulators, such as MOOSE (Permann et al., 2020), which are well-suited for capturing complex subsurface behavior. TANGO also supports the integration of commercial reservoir simulators for the subsurface component. While these tools often require simulator specific input/output formats, the flexible design of TANGO's computing unit allows for straightforward incorporation of such models.

For the economic component, the native model uses predefined cost correlations. For example, estimating drilling costs based on wellbore length and diameter. These correlations are derived from U.S. market data. To enhance flexibility and applicability across different regions, TANGO also supports user-defined models, allowing users to input custom cost correlations or assign scalar values directly. Importantly, extending TANGO to accommodate a new model is relatively straightforward due to the modular design.

3 NUMERICAL EXAMPLES

This section demonstrates the utility and flexibility of TANGO through several numerical examples encompassing applications to various geothermal systems with different levels of complexity.

3.1 Hydrothermal system

This subsection demonstrates the application of TANGO to doublet hydrothermal systems with two distinct surface facility designs: single-flash and double-flash power plants, as shown in Figure 2. The simulation framework integrates the subsurface reservoir, modeled using MOOSE, with the surface power plant, implemented via a native model based on TESPy (Witte et al., 2020), and the native model is used for the economic calculations. Key input parameters for the simulations, including subsurface properties and surface facility configurations, are summarized in the tables below. For simplicity, uniform reservoir properties are assumed.

The wells are spaced 707 meters apart (i.e. at the corners of a 1 x 1 km square), surface pipes have a 0.41 m diameter, and the system is operated at an mass flow rate of 45 kg/s. For economic parameters, the discount rate is set at 0.095, an OPEX cost fraction of 0.045, and a capacity factor of 0.9 is assumed.

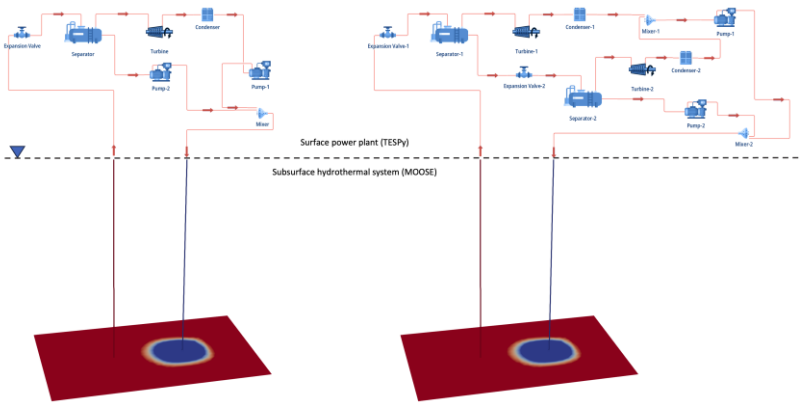


Figure 2: Illustration of hydrothermal systems with single flash (left) and double-flash power plant designs.

Table 2: Input parameters for the surface power plant

Parameter	Value	Unit
Surface temperature	15.0	deg. C
Turbine efficiency	0.78	-
Pipe diameter	0.41	m

Table 3: Input parameters for the subsurface

Parameter	Value	Unit
Reservoir depth	5000.0	m
Reservoir thickness	100.0	m
Permeability	100.0	mD
Porosity	0.2	-
Rock density	2650.0	kg/m^3
Rock specific heat capacity	1000.0	J/(kg-C)
Rock thermal conductivity	2.8	W/(m-deg. C)
Initial reservoir pressure	20,000	kPa
Initial reservoir temperature	323.0	deg. C

The techno-economic simulation results are summarized in Table 4. As expected, the double flash system shows higher energy extraction from the same geothermal reservoir. While the total capital cost for the double flash system is slightly higher, the substantial gain in electricity generation leads to a much lower LCOE. This example demonstrates TANGO's flexibility to simulate different power plant designs.

Table 4: Hydrothermal simulation results

Parameter	Total cost, million USD	Capacity, MWe	LCOE, $/MWh
Single flash	41.65	1.18	627.18
Double flash	43.25	2.48	309.61

3.2 CPG system

This subsection presents the techno-economic simulation results for CPG operations using TANGO. CPG is an emerging technology where CO_2 is utilized as a working fluid, instead of water, transforming CCS into CCUS (Randolph and Saar, 2011). In this study, we modeled a doublet CPG system using the native analytical models for all the components, including the surface power plant, injection well, reservoir, and production well. This approach is particularly suitable for quick site screening and potential evaluation studies. For the surface power plant, the direct system is assumed (Adams et al., 2021) (Figure 3). The input parameters for the wells and the

reservoir are summarized in the Table 5. The wells are spaced 707 meters apart (i.e. at the corners of a 1 x 1 km square), surface pipes have a 0.41 m diameter, and the system is operated at an mass flow rate of 100 kg/s. For economic parameters, the discount rate is set at 0.095, an OPEX cost fraction of 0.045, and a capacity factor of 0.9 is assumed.

Table 5: Input parameters for the subsurface

Parameter	Value	Unit
Reservoir depth	2500.0	m
Reservoir thickness	200.0	m
Permeability	50.0	mD
Porosity	0.2	-
Rock density	2650.0	kg/m^3
Rock specific heat capacity	1000.0	J/(kg-C)
Rock thermal conductivity	2.1	W/(m-deg. C)
Initial reservoir pressure	24,525.6	kPa
Initial reservoir temperature	102.0	deg. C

The simulation results demonstrate that TANGO is capable of evaluating the techno-economics of CPG power plants. However, the resulting total costs and capacity, given in Table 6, shows limited competitiveness. This is primarily due to the use of a simple doublet configuration. As noted in previous studies (e.g., Adams et al., 2021), the LCOE of CPG systems can be reduced by expanding to multi-well configurations, such as five-spot well patterns, which improve both thermal sweep efficiency and power output.

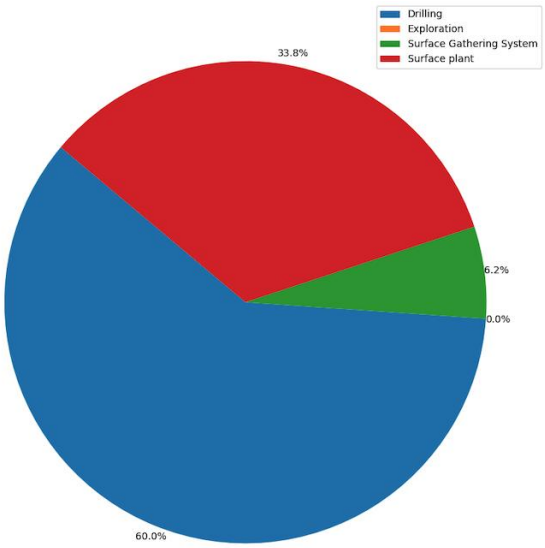


Figure 3: CPG simulation cost breakdown

Table 6: CPG simulation results

Total cost, MMUSD	Capacity, MWe	LCOE, $/MWh
15.6	0.67	465.40

3.3 EGS

The application of TANGO to EGS systems are presented by Chan et al., 2025. The readers are referred to the paper for more details.

4 CONCLUSION

We presented TANGO, a flexible techno-economic analysis software for geo-energy systems. The current software architecture and capabilities of TANGO were demonstrated through a series of numerical examples, including hydrothermal, CPG, and EGS systems. The key conclusions are as follows:

- A significant potential of TANGO in providing valuable insight into the evaluation of geo-energy operations for various purposes, ranging from quick site screening to in-depth simulation studies for specific sites of interest, has been demonstrated.
- The flexible framework and modular design allows for relatively easy implementation of new external software/tools using the computing/processing unit template.
- A suite of analysis tools, such as phase diagrams and statistical analysis, enable in-depth examination of the system at all points in the flow system.
- Physics-aware operational constraints enforce realistic operational limits, such as preventint bottom-hole pressures from reaching the fracture gradient.

Development of TANGO is an ongoing effort, and our future work includes supporting additional external simulators and the use of TANGO as a backend engine within a web application, enhancing usability and accessibility for a broader audience.

The Werner Siemens Foundation (Werner Siemens-Stiftung) is thanked for its support of the Geothermal Energy and Geofluids (GEG.ethz.ch) Group at ETH Zurich.

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