Techno-economic Analysis of Geo-energy Operations (TANGO), a new simulation tool

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ABSTRACT

Sustainable geo-energy technologies, including geothermal energy extraction, utilization, and conversion and subsurface thermal energy storage have significant potential to achieve international energy-sector decarbonization targets. Nonetheless, their widespread implementation is often hindered by technical feasibility and economic viability. Hence, conducting comprehensive techno-economic analyses is important when deploying these geo-energy systems.

While there exist simulation tools with techno-economic modeling capabilities, their flexibility and extendibility to various geo-energy systems remain limited. In this paper, we present TANGO, a new software application for Techno-economic ANalysis of Geo-energy Operations, which is an integrated techno-economic simulation tool designed to offer flexibility, allowing for a comprehensive evaluation of various geo-energy operations across different fidelity levels.

We demonstrate the application of TANGO to benchmark studies comparing the techno-economic potential of different geothermal systems. These examples range from rapid site screening to in-depth simulation studies, highlighting TANGO's versatility and utility in supporting decision-making across various stages of geo-energy system development.

1. INTRODUCTION

Sustainable geo-energy technologies, including geothermal energy extraction, subsurface hydrogen conversion/storage/retrieval, geologic carbon dioxide sequestration with/without simultaneous utilization, and aquifer thermal energy storage, in some cases combined, have long been recognized as essential elements in addressing the global decarbonization. Nevertheless, the implementation of these technologies often encounters challenges in terms of technical feasibility and economic viability. It is therefore imperative to conduct a comprehensive techno-economic analysis when deploying these technologies.

Numerous simulation tools and workflows have been developed for modeling specific components of geo-energy systems, including reservoir, wellbore, reservoir-wellbore coupled, and surface facility (Rasmussen et al., 2021; Pan and Oldenburg, 2014; Witte and Tuschy, 2020; Aspentech, 2024). However, relying solely on such tools tends to overlook the need for a comprehensive techno-economic evaluation of these integrated geo-energy systems. To address this gap, simulation tools with integrated techno-economic modeling capabilities have been developed. 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) are some of the notable existing techno-economic evaluation software for geothermal systems. While these powerful tools provide valuable insights into the techno-economic analysis of geothermal systems within their intended use cases, their flexibility and extendibility are often limited. Notably, they often rely on the pre-defined correlations based on unpublished ASPEN simulation results for traditional indirect power plants utilizing water as a working fluid for estimating electricity generation and costs for fixed surface facility designs, considerably limiting to prohibiting their applicability to diverse power plant designs, such as those involving emerging technologies like CO_2 Plume Geothermal (CPG) (Randolph and Saar, 2011). Additionally, for modeling subsurface flow and transport, these tools employ simple analytical models and/or specific numerical reservoir models, often assuming a single phase (aqueous). These assumptions restrict their applications to scenarios involving non-aqueous phases, as well as systems that do not require a reservoir model, such as those in advanced geothermal systems (AGS) (Malek, et al., 2022). Although possible, modifying the source code (updating the built-in reservoir/wellbore/surface components, developing a new I/O wrapper script for other external simulation tools, etc.) to accommodate different geothermal systems is not a trivial task. Similarly, in the realm of geologic CO_2 sequestration (GCS), tools with integrated modeling capabilities, such as the National Risk Assessment Partnership tool - Integrated Risk Assessment Model (NRAP-IAM) (Vasylkivska et al., 2021), are available. NRAP-IAM offers risk assessment capabilities accounting for various uncertainties with an integrated model for various subsurface components. However, it lacks economic calculation capabilities. More recently, GCS evaluation software with economic evaluation capabilities, such as SCO2T (Middleton et al., 2020), has been developed for rapid site screening considering various techno-economic uncertainties. While it excels in rapid site screening, its applicability for details modeling considering subsurface heterogeneity and multi-phase flow is limited. In summary, the existing tools excel in their designated applications. Our objective with the TANGO development is to create a versatile, user-friendly, general-purpose tool capable of adapting to diverse scenarios within geo-energy systems. The subsequent sections provide a more detailed description of TANGO, followed by a series of numerical examples.

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. Fig. 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 (Fig. 2). 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 Figs 1- 2). This is particularly beneficial when different units employ diverse models with specific input/output formats.

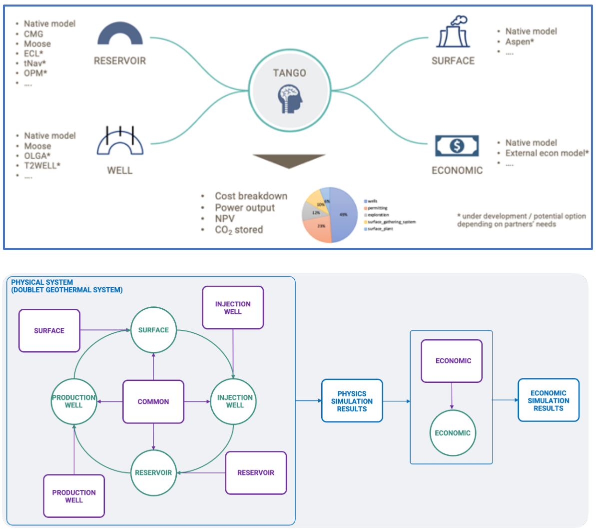

Figure 1: Graph-based representation of a doublet geothermal system

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 Figs 1- 2) 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.

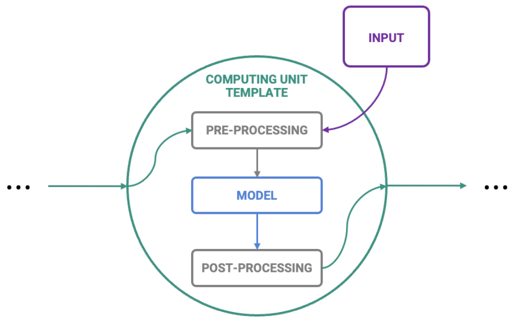

Figure 2: Graph-based representation of a doublet geothermal system

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

In this section, details of model options currently available (as of the time of writing) for various components within geo-energy systems summarized in Table 2 will be provided. The native built-in models are analytical models 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 (Figure 2) 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.

Table 2: Model options at different components

Section	Description
Reservoir	Native, Moose
Wellbore	Native, Moose
Surface	Native
Subsurface	(commercial) reservoir simulators
Economic	Native correlation, user defined

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. 3. 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.

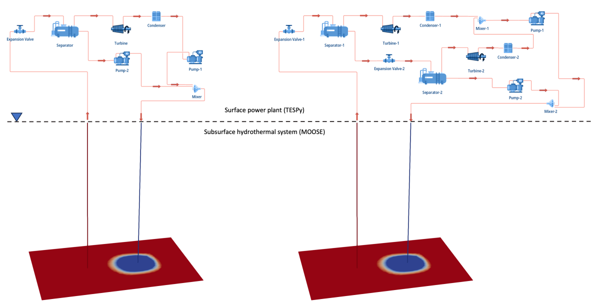

Figure 3: Illustration of hydrothermal systems with single flash (left) and double-flash power plant designs.

Table 3: 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 4: 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

Table 5: Operational parameters

Parameter	Value	Unit
Well spacing	707.0	m
Mass flow rate	45.0	kg/s
Project lifetime	20	years

Table 6: Economic parameters

Parameter	Value	Unit
Discount rate	0.095	-
OPEX cost fraction	0.045	-
Capacity factor	0.9	-

The techno-economic simulation results are summarized in Figure 4 and Table 7. 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.

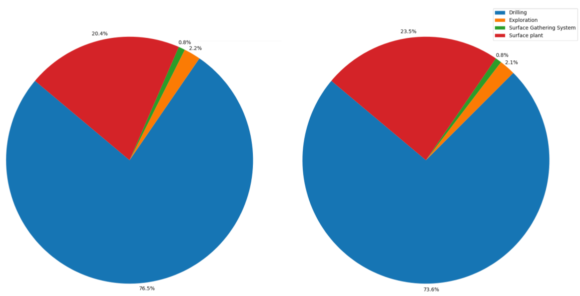

Figure 4: Hydrothermal simulation cost breakdown: single flash (left) and double flash (right)

Table 7: 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 6). The input parameters for the wells and the reservoir are summarized in the Table 8.

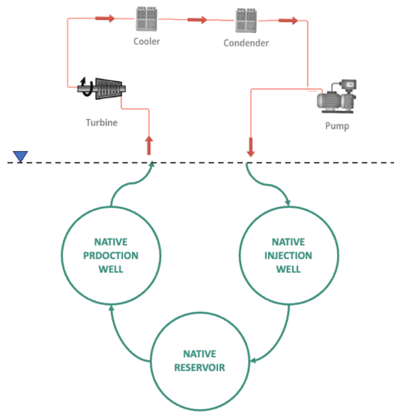

Figure 5: Illustration of CPG system using the native models

Table 8: 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

Table 9: Operational parameters

Parameter	Value	Unit
Well spacing	707.0	m
Mass flow rate	100.0	kg/s

Project lifetime	20	years

The simulation results demonstrate that TANGO is capable of evaluating the techno-economics of CPG power plants. However, the resulting LCOE 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.

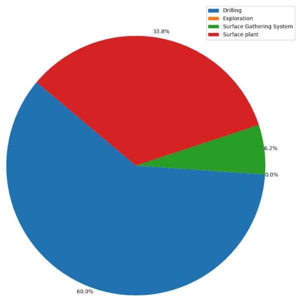

Figure 6: CPG simulation cost breakdown

Table 10: 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.

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 allows for relatively easy implementation of new external software/tools using the computing/processing unit template.

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.

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