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SAPHEA

INTEGRATING GEOTHERMAL HEATING AND COOLING NETWORKS IN EUROPE

D3.3 Summary report on the development and testing of the toolbox in the study areas

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Author: Ali Kök, TU Wien **/** C. Schifflechner, TUM **/** T. Seeger, TUM **/** M. Hajto, AGH University of Krakow **/** T. Olver **/** J. Brives, Geosphere Austria

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Verified by: Anna-Katharina Brüstle / Ardak Akhatova **/ Approved by:** Stefan Hoyer
Confidentiality level: Public
Contact: Ali Kök koek@eeg.tuwien.ac.at

www.saphea.eu

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Executive Summary

This report documents the development, validation, and testing of the SAPHEA decision support toolbox, with a particular focus on its Calculation Modules (CMs) for geothermal and large-scale heat pump systems. Implemented as a web-based GIS client, the toolbox brings together advanced spatial data management with robust techno-economic modelling tools, namely the SAPHEA GEOPHIRES and LSGEOHP (Large-scale Geothermal Heat Pump) modules. The report details the adaptation, integration, and workflow of these modules, ensuring transparency and usability for regional and municipal energy planning.

Validation of the SAPHEA GEOPHIRES module was undertaken using high-quality data from the Munich/Bavaria case study, confirming its technical reliability and alignment with established benchmarks. Further testing of the calculation modules was carried out in three additional study areas, Kraków, Cornwall, and Vienna, demonstrating the flexibility and adaptability of the toolbox in diverse geological and operational contexts. Results across all case studies consistently reflected plausible techno-economic outcomes and provided valuable feedback for continued refinement.

The findings of this deliverable highlight the SAPHEA toolbox's ability to support informed decision-making in early-stage geothermal project development. Lessons learned from the validation and testing phases have led to practical improvements in input handling, result presentation, and user documentation. The SAPHEA toolbox, freely accessible online, is now well-positioned for wider adoption and ongoing integration within the SAPHEA Market Uptake Hub.

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Introduction

Deliverable D3.3, "Summary Report on the Development and Testing of the Toolbox in the Study Areas", marks a pivotal milestone within WP3 of the SAPHEA project. This report brings together the comprehensive outcomes of two central activities: the rigorous validation of the SAPHEA GEOPHIRES calculation module using the Munich/Bavaria case study, and the subsequent testing of the toolbox across a diverse range of additional European locations, specifically Krakow (Poland), Cornwall (United Kingdom), and Vienna (Austria).

The motivation behind this deliverable lies in demonstrating the robustness and adaptability of the SAPHEA decision support toolbox for geothermal and large-scale heat pump systems. In an era of accelerating energy transition and increasing demand for reliable renewable heating solutions, the ability to provide transparent, replicable, and user-friendly modelling tools is essential for informed decision-making at both regional and municipal levels. D3.3 directly supports this aim by providing a clear record of how the Calculation Modules (CMs) have been adapted and integrated within the toolbox, as well as how they perform under a variety of real-world geological and operational conditions.

More specifically, this deliverable sets out to:

- Document the technical adaptation and seamless integration of the Calculation Modules (CMs) into the SAPHEA toolbox environment;
- Present detailed validation results from the Munich case study, which leveraged high-resolution, GIS-based datasets to benchmark the tool's performance; and
- Summarise the findings, insights, and lessons learned from subsequent testing in other regional contexts.

D3.3 is aligned with the objectives of Task 3.3, which focuses on data integration and thorough testing of the toolbox in designated project study areas, as well as Task 3.4, dedicated to product finalisation and comprehensive documentation. As such, this report also signifies the transition from the stages of module adaptation and iterative testing to the digital platform's readiness for broader deployment and user adoption.

The overarching focus of WP3 is to deliver an advanced decision support toolbox tailored for geothermal and heat pump systems at the district scale. By building on established open-source solutions such as Hotmaps [1], Citiwatts [2], EnerMaps [3], and GEOPHIRES [4], and by harnessing the power of GIS workflows, the SAPHEA toolbox aspires to become a cornerstone for strategic planning and investment evaluation in the renewable heating sector. The SAPHEA toolbox is freely accessible online at https://toolbox-saphea.eu/, enabling stakeholders, researchers, and planners across Europe to explore its features and capabilities. This deliverable, therefore, serves as a detailed record of the validation, testing, and iterative refinement phase that underpins this wider effort.

To guide the reader, the structure of this report is as follows:

- Section 2 describes the development and integration of the Calculation Modules within the SAPHEA toolbox.
- Section 3 details the validation process and results from the Munich/Bavaria case study.
- Section 4 presents the testing activities carried out in Kraków, Cornwall, and Vienna, including input parameters, results, and conclusions for each region.
- Section 5 discusses cross-cutting insights, lessons learned, and implications for future improvements.

Tool Development and Integration of Calculation Modules

The SAPHEA toolbox is implemented as a web-based GIS client, building upon the Hotmaps [1] framework, which offers a comprehensive suite of core spatial functionalities. These include features such as raster and vector layer management, advanced map navigation tools, and robust session control, all of which provide a versatile foundation for spatially enabled energy planning.

Within the SAPHEA toolbox interface, users begin by selecting a specific spatial region of interest, which may be defined using standard administrative units such as NUTS or LAU, or through custom-drawn polygons. Once a region has been selected, the platform automatically loads the relevant default datasets, ensuring that the analytical context is tailored to the user's spatial choice. Through the Calculation Modules tab, which is located within the Layers window, users are able to access and execute various modules, including the SAPHEA GEOPHIRES calculation module. The outputs from these modules are displayed both as dynamic map layers and as indicator charts within the Results panel, facilitating both spatial and quantitative interpretation. A complete guide on how to use the toolbox and a walkthrough of the calculation module sample runs are available on the SAPHEA Toolbox wiki page: https://saphea-project.github.io/wiki/welcome-to-saphea/.

This high level of spatial integration enables the modules to operate effectively with GIS-contextualised inputs, such as raster layers, thereby representing a significant advancement compared to conventional standalone calculation tools. In the background, the modules make use of spatial database layers similar to those provided by OpenStreetMap, which are hosted and managed via platforms such as PostGIS and GeoServer. In addition, key datasets are maintained and distributed through Git-based repositories, allowing for efficient integration, streamlined data management, and regular updates to reflect the evolving needs of users and stakeholders.

SAPHEA GEOPHIRES CM

The SAPHEA GEOPHIRES Calculation Module (CM) is a core element of the SAPHEA decision support toolbox, created to support the planning and evaluation of geothermal district heating and cooling (geoHC) networks across Europe. It integrates the GEOPHIRES (GEOthermal energy for Production of Heat and electricity Economically Simulated) [4] techno-economic simulation model into the SAPHEA platform, enabling detailed assessments of geothermal energy systems. Further technical and methodological documentation for the SAPHEA GEOPHIRES CM is available on its wiki page[1], and the open-source code, including both the stable 'main' branch and the active 'develop' branch, can be accessed at the GEOPHIRES Tuleap repository[2].

Originally released as a standalone simulation tool, GEOPHIRES calculates essential project metrics — including capital and operational expenditures, energy output, and levelized cost of energy (LCOE). Within the SAPHEA toolbox, it has been enhanced and adapted to:

- Simulate the direct use of hydro-geothermal resources for district heating setups,
- Seamlessly integrate with the Hotmaps [1] platform, enabling users to populate input parameters through a user-centric interface,
- Present results in multiple formats to support informed decision-making,
- Facilitate scenario analysis, allowing users to alter input parameters and evaluate various geoHC development approaches.

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[1] https://saphea-project.github.io/wiki/cm-geophires/

[2] https://vlhtuleap.hevs.ch/plugins/git/saphea/saphea_geophires?a=tree&hb=main

This CM is designed to make geothermal project evaluation more accessible, transparent, and adaptable to diverse regional contexts. Figure 1 shows the screenshot of the Calculation Module section of the SAPHEA Toolbox below. Detailed information regarding the Toolbox can be found in D3.2.

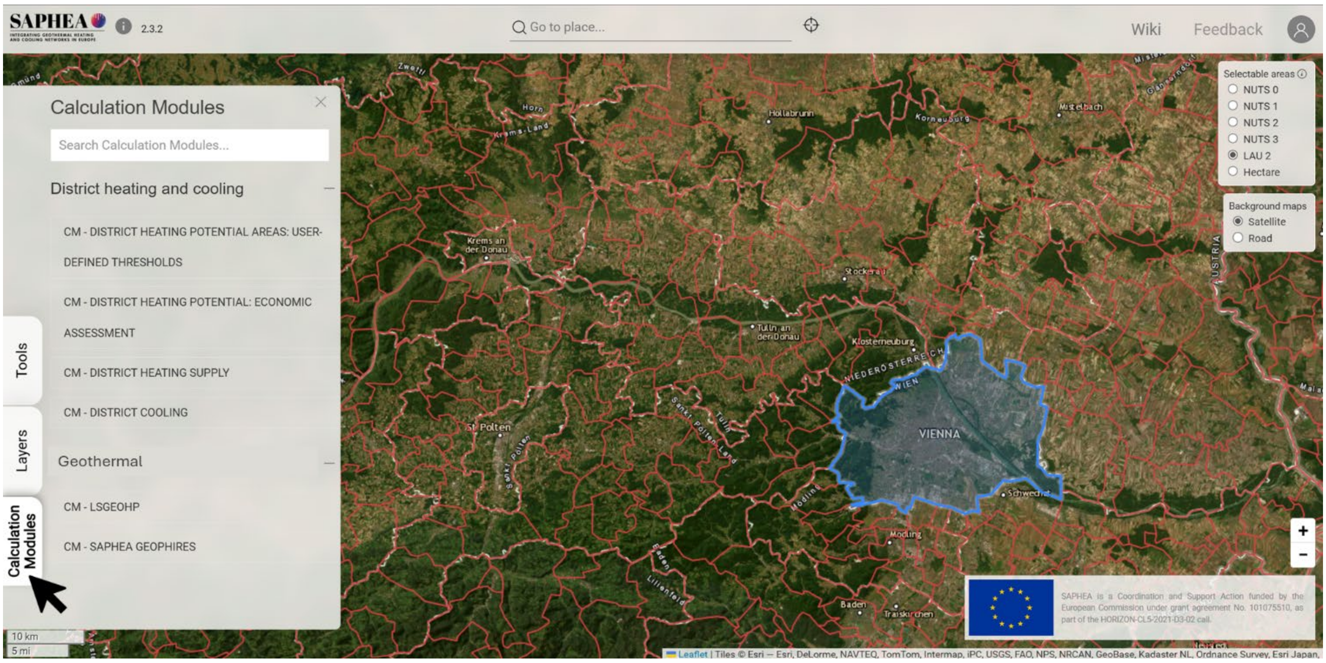

Figure 1: Screenshot of the Calculation Module Tab in the SAPHEA Toolbox

The SAPHEA GEOPHIRES CM adapts GEOPHIRES v2.0 [5], incorporating reservoir models, well hydraulics, and techno-economic calculations to estimate reservoir behaviour, capital and operational costs, and Levelized Cost of Heat (LCOH). GEOPHIRES v2.0 is adapted specifically for **deep hydro-geothermal** implementations.

The following improvements have been made to increase the user-friendliness of the tool based on user feedback:

1. **Integration of advanced input handling, introducing default and validated default values for input parameters**

– GEOPHIRES v2.0 [5] accepts only text files as input files. This makes the preparation of input files time-consuming and not easily tractable. After receiving feedback for a more user-friendly input preparation during the testing phase, GEOPHIRES v2.0's native input handling procedure is integrated into the user interface (UI) of the SAPHEA Toolbox. In this way, users can provide their inputs via input boxes on the UI or CSV uploads.

– Based on literature reviews, expert surveys, and GEOPHIRES v2.0's [5] own documentation, default values are provided for each user input.

2. **Output file generation logic updates, introducing the Excel and text export workflows.**

– GEOPHIRES v2.0 [5] provides results as a report in text format. User feedback has shown that even though the results are easy to read, the number of categories may become overwhelming. On the other hand, it is not easy to do a numerical analysis on the text file or import it into another software program for further analysis. In order to present the results in a more user-friendly manner, the core technical and economic results are selected based on user feedback and expert views. These selected core results are presented on the user interface right after the CM is run, allowing a quick screening of the most important results.

– Detailed results are grouped into a summary and a detailed results report, both available in text and Excel file formats. While the text files make it easier to screen numerous results parameters, the Excel files contain the same information grouped into several sheets. The Excel outputs allow users to store and document their results, and make it possible to do quick analysis or import the data to other software programs for further analysis.

Calculation Module Inputs

To balance usability and configurability, inputs are organised into three progressively advanced categories. While the first category consists of the core input parameters, the second category involves more advanced technical and operational parameters. Finally, the last category consists of cost adjustment factors allowing the users to scale specific cost components.

Organising inputs into tiers allows beginners to run standard simulations with minimal effort, while advanced users can refine cost models and increase fidelity. Outputs span technical (temperatures, power) and economic (CAPEX, OPEX, LCOH) indicators, with downloadable summaries for reporting and further analysis. This design aligns with SAPHEA's goal of delivering transparent, regionally adaptable, and user-friendly geothermal evaluation tools.

1. **(Core) Inputs – define the geothermal resource and wellfield parameters**

Input Name	Unit	Default	Min	Max	Description
Reservoir Depth	km	3	1.5	5.0	Depth of the geothermal reservoir
Gradient	°C/km	30	0.0	500.0	Temperature increase per km in reservoir
Number of Production Wells	–	1	1	20	Identical production wells count
Number of Injection Wells	–	1	1	20	Identical injection wells count
Production Flow Rate per Well	kg/s	50	1.0	500.0	Fluid flow through each production well
Injection Temperature	°C	40	0.0	200.0	Temperature of reinjected fluid at the reservoir input

2. **Basic (Operational) Inputs – represent operational performance and plant factors**

Input Name	Unit	Default	Min	Max	Description
Productivity Index	kg/s/bar	10	0.0	10.0	Production flow rate per pressure drop
Injectivity Index	kg/s/bar	10	0.01	1000.0	Injection flow rate per pressure drop
Surface Temperature	°C	10	–50	50	Temperature at wellhead/surface baseline
End-Use Efficiency Factor	–	0.9	0.1	1.0	Efficiency of heat delivery/utilisation
Utilization Factor	–	0.6	0.1	1.0	The fraction of the year the plant operates. Equivalent of the capacity factor.
Plant Lifetime	years	30	1.0	100.0	Duration of plant operation
EUR–USD Exchange Rate	–	1.09	0.1	10.0	Currency conversion rate
Discount Rate	–	0.04	0.0	1.0	Used in economic discounting

3. Advanced Inputs – provide customisation of economic assumptions:

Input Name	Unit	Default	Min	Max	Description
Well Drilling and Completion Capital Cost Adjustment Factor	–	1	0.0	10.0	Scales built-in well drilling and completion capital costs
Reservoir Stimulation CapEx Adjustment Factor	–	1	0.0	10.0	Adjusts base stimulation capital costs
Surface Plant CapEx Adjustment Factor	–	1	0.0	10.0	Scales surface plant CAPEX
Field Gathering System CapEx Adjustment Factor	–	1	0.0	10.0	Scales wellfield infrastructure costs
Exploration CapEx Adjustment Factor	–	1	0.0	10.0	Adjusts geological/exploration expenditure
Wellfield O&M Cost Adjustment Factor	–	1	0.0	10.0	Scales annual wellfield O&M
Surface Plant O&M Cost Adjustment Factor	–	1	0.0	10.0	Scales annual surface plant O&M
Water Cost Adjustment Factor	–	1	0.0	10.0	Scales make up water cost
Electricity Rate	EUR/kWh	0.1	0.01	10.0	Used to calculate the pumping/electricity cost

CM Outputs

When a simulation is finished, the SAPHEA GEOPHIRES module produces a wide range of outputs that provide information on the geothermal system's technical and financial performance. These results are accessible via the SAPHEA platform and can be downloaded in different formats.

1. Platform indicators

Key performance indicators (KPIs) are displayed within the SAPHEA platform to provide a brief summary of the simulation results.

Output Indicator	Unit	Description
LCOH	EUR/MWh_th	Levelised cost per megawatt-hour of heat
Drilling & Completion Costs	MEUR	Total CAPEX for all wells
Average Drilling Cost per Well	MEUR	Cost per individual well
Stimulation Costs	MEUR	CAPEX for reservoir stimulation
Surface Plant Costs	MEUR	CAPEX for heat plant infrastructure
Gathering System Costs	MEUR	Surface transport system infrastructure CAPEX
Total Surface Equipment Costs	MEUR	Combined surface infrastructure CAPEX
Exploration Costs	MEUR	Geological/exploration CAPEX
Total Capital Costs	MEUR	Sum of all investment costs
Wellfield O&M Costs (annual)	MEUR/yr	Operating expenditures in the wellfield
Surface Plant O&M Costs (annual)	MEUR/yr	Operating expenditures for surface plant
Make-Up Water O&M Costs (annual)	MEUR/yr	Cost of replacement water
Avg. Annual Pumping Power	MW_e	Electric energy required for operation
Bottom-Hole Temperature	°C	The temperature in the reservoir below the surface
Avg. Production Well Temperature Drop	°C	Cooling of fluid while reaching the surface
Avg. Pump Pressure Drops (injection/production)	kPa	Hydraulic losses in wells

2. Additional Output Files

In addition to the platform's immediate performance indicators, the CM also produces two comprehensive output files for in-depth review and further analysis:

- **Text Report (.txt)**

  A detailed textual record that captures everything from input values to simulation outputs. This includes a line-by-line breakdown of costs, energy production metrics, and economic performance indicators, making it easy to trace and validate model calculations.

- **Excel Report (.xlsx)**

  A fully structured spreadsheet that aggregates all data generated during the simulation. It includes multiple tabs for easy navigation and supports visualisation, further manipulation, or integration with other analytical tools.

These files collectively cover:

- Input Parameters — a complete listing of both user-entered and default settings used during simulation
- Production Profiles — time series data of heat output, reservoir temperatures, and flow rates
- Cost Breakdown — granular capital and operational cost components, such as drilling, surface plant, and gathering infrastructure
- Economic Analysis — calculation outputs for Levelised Cost of Heat (LCOH), embedding all financial assumptions and performance data

These downloadable reports offer full transparency and support deeper technical evaluation, documentation, or stakeholder communication.

Large-Scale Geothermal Heat Pump CM

The Large-Scale Geothermal Heat Pump (LSGEOHP) CM is developed within the SAPHEA project based on user feedback indicating a need for the use of deep/medium-deep geothermal energy in combination with large-scale heat pumps. A comprehensive user guide, technical background, and example scenarios for the LSGEOHP CM are available on its wiki page[3], and the calculation module's open-source codebase (covering both 'main' and 'develop' branches) can be found in the Tuleap repository[4].

The LSGEOHP calculation module serves as an early-stage assessment tool for large-scale geothermal heat pump systems, helping users estimate key performance metrics such as thermal output, coefficient of performance (COP), and investment costs. It delivers an initial, approximate evaluation that relies on simplified assumptions—previewing system viability rather than replacing the need for thorough, project-specific engineering design and analysis.

It is tailored specifically for medium to deep geothermal applications, augmented with large-scale heat pumps, intended for district or community heating systems. It supports three distinct deployment scenarios:

1. **Direct use**: where geothermal fluids already match district heating network temperatures,
2. **Capacity increase**: where the geothermal fluid temperature already covers the DH network needs, and a large-scale heat pump is used to increase the total heating capacity.
3. **Temperature boost**: where the geothermal production temperature is not sufficient to directly supply heat to the DH network, and the production temperature is lifted by the large-scale heat pump to enable district heating use.

The efficiency of a compression heat pump is defined by its coefficient of performance (COP)—the ratio of the useful heat output (for instance, the heat delivered to a district heating network) to the electrical energy required to operate the system, primarily consumed by the compressor. For example, a COP of 4 indicates that 1 kWh of electricity can be used to produce 4 kWh of usable heat at the desired temperature level. As such, a higher COP directly translates into lower operational costs, especially in terms of electricity consumption.

However, thermodynamic constraints limit the maximum achievable COP. A key factor is the temperature lift, which refers to the difference between the low-temperature source (e.g., geothermal brine) and the high-temperature sink (e.g., DHN). As the temperature lift increases, the maximum theoretical COP decreases. This relationship is illustrated in the corresponding performance diagram. The Carnot COP defines the upper thermodynamic boundary, but in real-world applications, actual heat pumps typically operate at around 40% to 50% of this ideal value. This module provides users with the COP values closer to actual COPs observed in real life instead of the theoretical Carnot COP.

Figure 1 illustrates three different scenarios for the use of medium-deep/deep geothermal energy, of which large-scale heat pumps can serve in two main scenarios for geothermal heating systems:

- Increasing the thermal capacity of an existing geothermal installation,
- Lifting the temperatures of geothermal sources with insufficient production temperatures.

[3] https://saphea-project.github.io/wiki/cm-large-scale-geothermal-heat-pump/

[4] https://vlhtuleap.hevs.ch/plugins/git/saphea/saphea_geophires?a=tree&hb=main

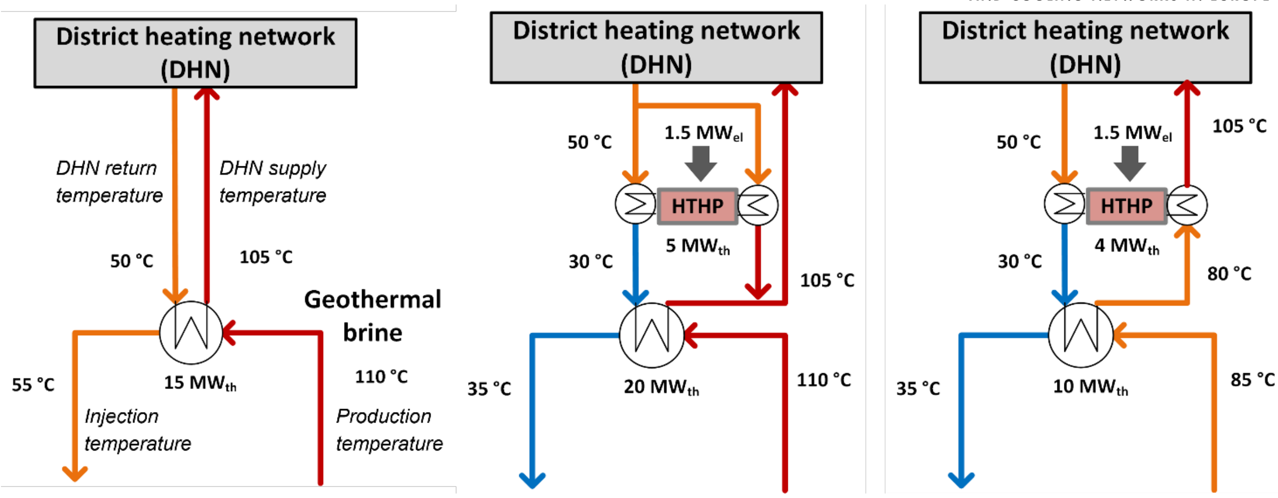

Figure 2: Illustration of the working principle of geothermal energy in combination with a high-temperature heat pump

Direct use without a heat pump: In this configuration, the geothermal brine is produced at a sufficiently high temperature—typically around 110 °C—which allows it to supply the district heating network (DHN) directly at the required temperature (e.g., 105 °C). Once heat is transferred to the DHN, the cooled brine is reinjected into the reservoir. This approach is both efficient and straightforward, as it does not require any additional thermal upgrading. However, it is only viable when the geothermal resource can consistently provide high production temperatures. This scenario is covered in more detail by the SAPHEA GEOPHIRES CM.

Capacity increase using a heat pump: In this case, the production temperature of the geothermal brine is still relatively high, allowing for direct heat transfer to the DHN. However, instead of reinjecting the partially cooled fluid, a high-temperature heat pump (HTHP) is installed to extract additional thermal energy from the residual heat. The pump raises the temperature of this lower-grade heat so it can also be used in the DHN, thereby increasing the overall thermal capacity of the system without requiring additional wells or higher flow rates.

Use of low-temperature geothermal resources with a heat pump: In the third and more conventional scenario, the geothermal brine is produced at a lower temperature—typically between 85 °C and 90 °C—which is not sufficient for direct use in the DHN. Here, the installation of a large-scale heat pump becomes essential. The heat pump draws energy from the moderately warm brine and boosts it to the temperature level required by the DHN. Without such temperature upgrading, the geothermal resource would not be suitable for district heating in this context.

The LSGEOHP Calculation Module is designed to operate in two different environments, providing flexibility for users depending on their workflow or platform access. Two different operating modes of the calculation model are illustrated in Figure 2.

Integrated Use within the SAPHEA Toolbox

The module is fully embedded in the SAPHEA decision support platform, accessible through the “Calculation Modules” tab in the left-hand panel of the interface. Users can select a geographic region on the map, choose the CM-LSGEOHP from the list, and input required parameters directly through a guided interface. This integrated version aligns the module with SAPHEA’s GIS-based interface, allowing users to simulate systems in a spatial context, even though the CM itself does not rely on spatial data layers.

Standalone HTML Tool

Alternatively, the LSGEOHP CM is available as a standalone HTML file that can be run directly in a web browser without accessing the full SAPHEA platform. This version provides the same core functionality—scenario selection, parameter input, and result display—in a lightweight, platform-independent format. It is particularly useful for testing, teaching, or conducting quick analyses outside of the main GIS interface.

In both environments, the user interface is identical in structure, and all calculations are executed locally in the browser. The standalone option also facilitates easier demonstration and can be shared directly via a link or local file.

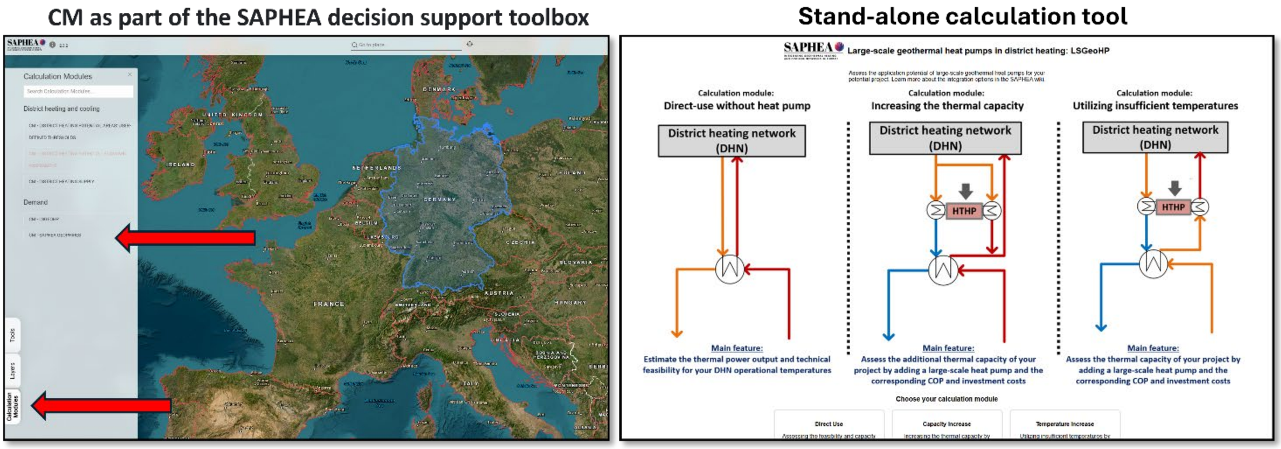

Figure 3: Accessing the tool within SAPHEA Toolbox vs the standalone version

Calculation Module Inputs

In LSGEOHP CM, the input parameters are not organised into several categories since the number of parameters is relatively low.

The table below shows the input parameters commonly used in all the scenarios.

Input Name	Unit	Description
Geothermal brine mass flow rate	kg/s	Mass flow rate of the geothermal fluid
Geothermal production temperature	°C	Temperature of the fluid at the production wellhead
Geothermal injection temperature	°C	Temperature of reinjected fluid; in direct-use, constrained by DHN return
DHN supply temperature	°C	Required supply temperature of the district heating network
DHN return temperature	°C	Return network temperature, based on customer structure

The table below shows the input parameters required only for the capacity increase scenario.

Input Name	Unit	Description
Injection temp without heat pump (optional)	°C	Estimated reinjection temp without heat pump usage
Minimal feasible injection temperature	°C	Operational lower threshold for injection fluid

CM Outputs

Once the required input parameters are entered and the scenario is selected, the LSGEOHP CM performs the simulation and provides a summary of key performance and economic indicators. The results are presented directly within the platform interface and allow users to assess the technical feasibility and economic characteristics of the selected system configuration.

The output values include the total amount of thermal energy delivered to the district heating network (DHN), the proportion of heat sourced directly from the geothermal resource, and the additional contribution provided by the heat pump. The module also reports the electrical power required to drive the heat pump, the achieved coefficient of performance (COP), and an estimate of the specific investment cost associated with the heat pump unit.

The following table provides an example of the output generated for a scenario where the geothermal source temperature is sufficiently high to allow direct supply to the DHN, and a heat pump is used to increase the system's thermal capacity:

Output Parameter	Unit	Description
Scenario	–	Indicates which scenario is implemented based on the user inputs (only available in the integrated version)
Total Heat Delivered to DHN	MW_th	Combined heat output supplied to the district heating network
Geothermal Heat Input	MW_th	Thermal energy extracted directly from the geothermal source
Heat Pump Output	MW_th	Additional heat supplied by upgrading the lower-temperature brine
Electrical Power Consumption	MW_el	Electricity required to operate the heat pump
Coefficient of Performance (COP)	–	Ratio of heat pump output to electricity input
Specific Investment Cost of Heat Pump	EUR/MW_th	Investment cost per unit of heat pump thermal output capacity

Validation of SAPHEA GEOPHIRES

Munich/Bavaria Case Study

The Munich/Bavaria case study served as the validation benchmark for the SAPHEA GEOPHIRES Calculation Module (CM), due to the availability of high-quality geothermal datasets and previously published simulation results. In contrast to the other study regions, Bavaria offered both a well-documented geological reservoir model and a set of GIS-based inputs provided by the local geological service and project partners. The objective was to evaluate the technical consistency and accuracy of the SAPHEA GEOPHIRES CM by comparing its outputs against those from a pre-existing regional energy planning tool developed during a local master's thesis.

The Bavarian Molasse Basin provides hydrothermal potential for deep geothermal energy in Southern Bavaria. The targeted reservoir harbours a fractured karst pore aquifer located in the carbonate rocks of the Upper Jurassic (Malm Reservoir) in depths between 2,000 and 3,000 m in the Munich area and up to 5,000 m in the southernmost area of the reservoir [6]. With temperatures up to 160 °C and generally high permeability resulting in high mass flow rates, it offers favourable conditions for direct hydrothermal usage. As of 2024, 25 geothermal plants have been successfully implemented in this region, supplying heat primarily to district heating networks.

Within the Masterplan Geothermie Bayern 2025, potential scenarios for the expansion of deep geothermal energy within the Bavarian Molasse Basin have been evaluated by TU Munich, ensuring optimal utilisation of the reservoir whilst also including the techno-economic effects of constructing additional district heating networks. Input and output data of these scenarios will be used for validating the resulting calculations of GEOPHIRES.

Input data for SAPHEA GEOPHIRES provided by the Bavarian case study

Raster layers for the following parameters have been provided for calculations:

- discharge temperatures (°C),
- discharge flow rate (l/s) representing probabilities p10, p25, p50, p75, p90,
- reservoir depth (m),
- reservoir thickness (m).

Table 1: Values provided for Munich Case Study calculation in GEOPHIRES

Parameter	Unit	Input	Reference
Injection temperature	°C	50	Molar-Cruz et al., 2022 [8]
Reservoir heat capacity	J/kg*K	4,203	Molar-Cruz et al., 2022 [8]
Bulk density	kg/m³	2,590	mean value through logging data
Thermal water density	kg/m³	996	Molar-Cruz et al., 2022 [8]
Thermal conductivity	W/m*K	3.71	mean value through logging data
Productivity / Injectivity Index	l/s*bar	9.22	mean value through logging data

[5] The Masterplan Geothermie Bayern 2020 was published as a detailed German Research Report [6] and an English peer-reviewed journal article [8].

Parameter	Unit	Input	Reference
Pump efficiency	-	0.85	Schlagermann 2014 [9]
Annuity (25 years, 5 %)	-	0.07095	Molar-Cruz et al., 2022 [8]
Full load hours	h	4,050	Molar-Cruz et al., 2022 [8]
Production well diameter	inch	8.5	-
Injection well diameter	inch	8.5	-

Output data from GEOPHIRES

The output data from GEOPHIRES was compared to the results of Masterplan Geothermie 2020 within five locations in the greater area of Munich (MUC-Plus, Figure 1). The locations represent different discharge temperatures, depths and discharge zones of the reservoir.

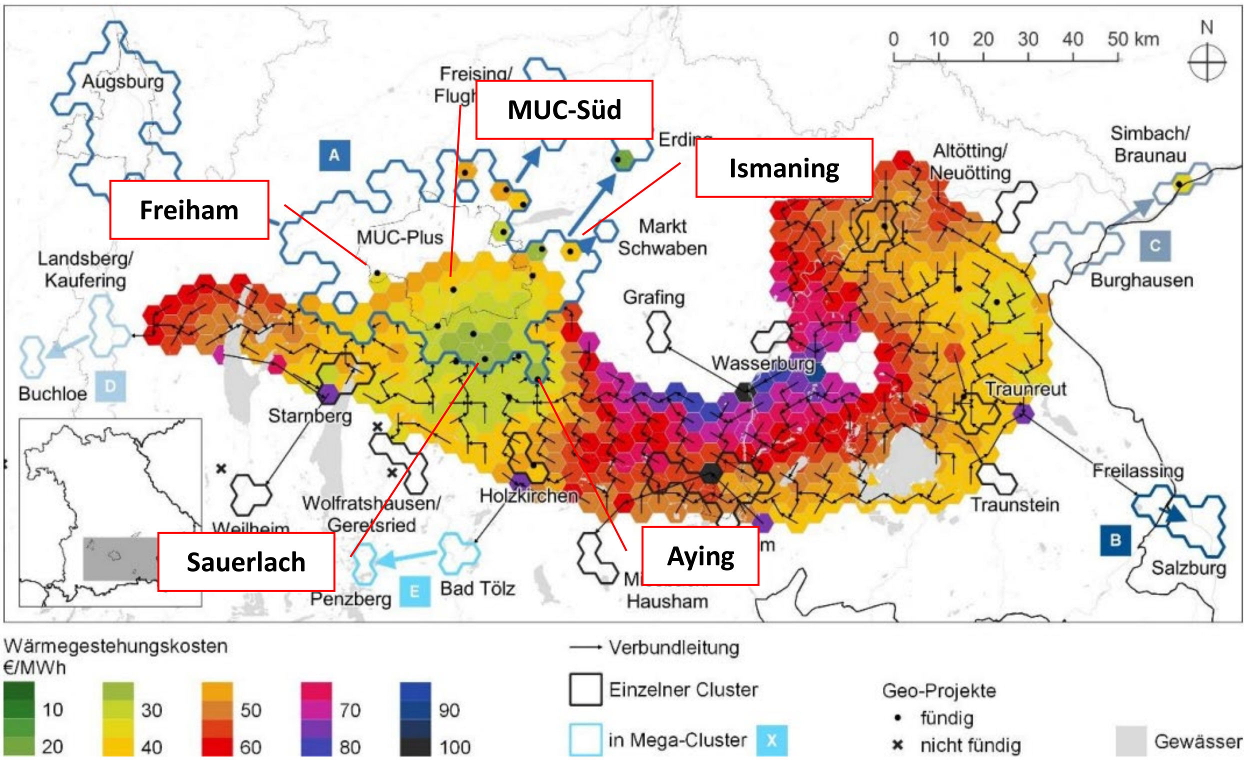

Figure 4: Heat production costs per hydrothermal doublet (e.g. hexagonal rasters) for 100 % coverage of the heat demand for Southern Bavaria [7].

Principally, results by GEOPHIRES (Table 2-Table 6) show an increase in heat production parallel to an increase in flow rate and temperature. Heat production costs, quantified by the levelized costs of heat (LCOH), decrease with an increase in heat production, rightfully, since the main factor for CAPEX, drilling costs, respectively, costs for development of the reservoir stay constant through similar depths.

In Keim et al. (2020) [6], heat production and LCOH have been calculated based on a fixed discharge flow rate for each discharge zone. For GEOPHIRES heat production and heat production costs have been calculated for each probability of flow rate in the respective raster of each location, hence, the comparable results are situated in the range between p25 and p50.

Comparing the results, the calculated heat production by GEOPHIRES is situated in a value range which is acceptable and confirms the validity of the GEOPHIRES tool for the South German Molasse Basin. Since the actual potential is not known until the reservoir is tapped, the calculated potential should not be presented in a single value anyway, but rather divided into a range of values, for example, according to worst-case, business-case and best-case scenarios. Regarding LCOH, results from GEOPHIRES for Sauerlach, München-Süd and Ismaning are in an acceptable range. For locations Freiham and Aying, LCOH are by at least a quarter, respectively, a fifth higher compared to the results in Masterplan Geothermie. For Freiham, this could possibly be related to a mistakenly different input to depth by an additional 200 m. Therefore, also for the economic assessment, the developed GEOPHIRES tool can be validated for the South German Molasse Basin.

Table 2: Results for heat production and heat production costs for location Sauerlach

Location		**Sauerlach**		
discharge zone		**Zone IIIa**		
Parameter	**Unit**	**MAP Geo.**	**p25 GEOPH.**	**p50 GEOPH.**
discharge flow rate	l/s	80	66	103
discharge temperature	°C	143	143	143
heat production	MW_{th}	20 - 25	22	35
heat production costs	€/MWh_{th}	20 - 30	35	28

Table 3: Results for heat production and heat production costs for location München-Süd

Location		**München-Süd**		
discharge zone		**Zone Ia**		
Parameter	**Unit**	**MAP Geo.**	**p25 GEOPH.**	**p50 GEOPH.**
discharge flow rate	l/s	90	70	115
discharge temperature	°C	100	100	100
heat production	MW_{th}	15 - 20	13	21
heat production costs	€/MWh_{th}	30 - 40	34	30

Table 4: Results for heat production and heat production costs for location Ismaning

Location		**Ismaning**		
discharge zone		**Zone Ia**		
Parameter	**Unit**	**MAP Geo.**	**p25 GEOPH.**	**p50 GEOPH.**
discharge flow rate	l/s	90	70	115
discharge temperature	°C	73	73	73
heat production	MW_{th}	5 - 10	6	10
heat production costs	€/MWh_{th}	40 - 50	70	50

Table 5: Results for heat production and heat production costs for location Freiham

Location		Freiham		
discharge zone		**Zone Ia**		
Parameter	**Unit**	**MAP Geo.**	**p25 GEOPH.**	**p50 GEOPH.**
discharge flow rate	l/s	90	70	115
discharge temperature	°C	83	83	83
heat production	MW_{th}	10 - 15	8	14
heat production costs	€/MWh_{th}	30 - 35	53	43

Table 6: Results for heat production and heat production costs for location Aying

Location		Aying		
discharge zone		**Zone IIb**		
Parameter	**Unit**	**MAP Geo.**	**p25 GEOPH.**	**p50 GEOPH.**
discharge flow rate	l/s	70	66	103
discharge temperature	°C	121	121	121
heat production	MW_{th}	20 - 25	17	27
heat production costs	€/MWh_{th}	20 - 30	45	36

Testing of SAPHEA GEOPHIRES

Following the validation phase in Munich, the SAPHEA GEOPHIRES CM was tested in three additional case study regions: Kraków (Poland), Cornwall (United Kingdom), and Vienna (Austria). These tests aimed to assess the tool's flexibility and usability in diverse geological, climatic, and infrastructural contexts, using representative data provided by project partners.

Unlike the Munich validation, where detailed GIS data were available, these studies relied on single-point parameter entries representing typical geothermal configurations. This approach reflects a realistic use case for planners conducting preliminary assessments in data-scarce environments.

Each case study followed a standardised procedure:

- Configuration of inputs in the standalone version of SAPHEA GEOPHIRES and/or integrated version in the SAPHEA toolbox,
- Running the CM and exporting the results,
- Interpretation by local experts with contextual understanding,
- Comparison with regional expectations or previous assessments,

Kraków Case Study (Poland)

The lack of oil exploration activity within Kraków limits the availability of geological and hydrogeological data essential for a reliable assessment of its geothermal potential. Scarce borehole geophysics or seismic studies have been conducted in the area. However, some relevant geological data emerged east of Kraków, prompting the drilling of several deep boreholes in the city's Nowa Huta district. As a result, most of Kraków's knowledge of deep geothermal potential comes from oil wells drilled in the late 1960s. Regional studies and published findings indicate that this area holds promise for deep geothermal exploration. Lithological and stratigraphic analyses suggest that potential geothermal water reservoirs are mainly associated with Middle and Upper Devonian (D2+D3) limestones and dolomites, while the Upper Jurassic carbonate formations (J3) appear less promising, providing mineral waters on a semi-regional scale. Despite this potential, geothermal water has not yet been exploited in Kraków. To advance geothermal energy development, the Kraków municipality has secured a subsidy grant and plans to drill a deep geothermal well reaching approximately 1,800 meters, with a screened interval between 1,500 and 1,800 meters. Drilling is expected to begin around late 2025 or early 2026.

Table 7: User inputs used and model results received for the Krakow case study.

Primary Parameters Used for Testing	**1st Run** *Simulation Date 2025-01-24*	**2nd Run** *Simulation Date 2025-02-19*	**3rd Run** *Simulation Date 2025-02-19*
• **Reservoir Depth**: Depth of the reservoir (unit: km)	1.5 (top)	1.5 (top)	1.5 (top)
• **Well Depth**	1800.0 m	1800.0 m	1800.0 m
• **Number of segments**: Number of segments from surface to reservoir depth with specific geothermal gradient (allowable values: [1,2,3,4])	4	4	4

• **Gradient 1**: Geothermal gradient in segment 1 (unit: °C/km)	21	21	21
• **Gradient 2**: Geothermal gradient in segment 2 (unit: °C/km) ○ It is possible to provide up to 4 different gradients	25	25	25
• **Gradient 3**: Geothermal gradient in segment 3 (unit: °C/km)	28	28	28
• **Gradient 4**: Geothermal gradient in segment 4 (unit: °C/km)	23	23	23
• **Thickness 1**: Thickness of segment 1 (unit: km)	0.41	0.41	0.41
• **Thickness 2**: Thickness of segment 2 (unit: km) ○ It is possible to provide up to three thicknesses (the last one will be calculated based on the reservoir depth)	0.29	0.29	0.29
• **Thickness 3**: Thickness of segment 3 (unit: km)	0.8	0.8	0.8
• **Thickness 4**: Thickness of segment 4 (unit: km)	0.3	0.3	0.3
• **Production Flow Rate per Well**: Geofluid flow rate per production well (unit: kg/s)	17 (~55 m^3/h)	17 (~55 m^3/h)	17 (~55 m^3/h)
• **Injectivity Index**: Injectivity index defined as ratio of injection well flow rate over injection well outflow pressure drop (unit: kg/sec/bar)	8	8	8
• **Productivity Index**: Productivity index defined as the ratio of production well flow rate over production well inflow pressure drop (unit: kg/sec/bar)	8	8	8
• **Injection Temperature**: Constant geofluid injection temperature at injection wellhead (unit: °C)	5	5	5
• **Utilisation Factor**: Ratio of the time the plant is running in normal production in a 1-year time period (allowable value range: [0.1,1])	1	1	1
• **Plant Lifetime**: System lifetime (unit: years)	50	25	25
• **Discount Rate**: Discount rate used in the Standard Levelized Cost Model (allowable value range: [0.1,1])	0.07	0.07	0.07
Optional parameters used for the testing. Default values are used where no data is available.			
• **Production Well Diameter**: Inner diameter of production wellbore (assumed constant along the wellbore) (unit: inches)	6 1/4	6 3/4	8
• **Injection Well Diameter**: Inner diameter of injection wellbore (assumed constant along the wellbore) (unit: inches)	6 1/4	6 3/4	8
• **Reservoir Volume**: Geothermal reservoir volume (unit: m^3)	1e+9	1e+9	1e+9

• **Reservoir Density**: Constant and uniform reservoir density (unit: kg/m^3)	2590	2590	2590
• **Reservoir Heat Capacity**: Constant and uniform reservoir heat capacity (unit: J/kg/K)	920	920	920
• **Reservoir Thermal Conductivity**: Constant and uniform reservoir thermal conductivity (unit: W/m/K)	3.5 (reservoir only)	3.5 (reservoir only)	3.5 (reservoir only)
• **Circulation Pump Efficiency**: Specify the overall efficiency of the injection and production well pumps (allowable value range: [0.1,1])	0.85	0.85	0.85
• **Surface Temperature**: Surface temperature used for calculating bottom-hole temperature (with geothermal gradient and reservoir depth) (unit: °C)	10	10	10
• **Ambient Temperature**: Ambient (or dead-state) temperature used for calculating power plant utilisation efficiency (unit: °C)	15	15	15
• **End-Use Efficiency Factor**: End-Use Efficiency Factor (allowable value range: [0.1,1])	0.9	0.9	0.9
• **Electricity Rate**: Price of electricity to calculate pumping costs (unit: €/kWh)	0.19	0.19	0.19
• **Cost Adjustment Factors**:			
○ Reservoir Stimulation Capital Cost: Total reservoir stimulation capital cost (unit: M€/year)	1	1	1
○ Surface Plant Capital Cost: Total surface plant capital cost (unit: M€/year)	1	1	1
○ Field Gathering System Capital Cost: Total field gathering system capital cost (unit: M€/year)	1	1	1
○ Exploration Capital Cost: Total exploration capital cost (unit: M€/year)	1	1	1
○ Wellfield O&M Cost: Total annual wellfield O&M cost (unit: M€/year)	1	1	1
○ Surface Plant O&M Cost: Total annual surface plant O&M cost (unit: M€/year)	1	1	1
○ Water Cost: Total annual make-up water cost (unit: M€/year)	1	1	1
Simulation Results			
Surface Equipment Simulation Results			
○ Average Net Heat Production (MWth)	3.08	3.07	3.07
○ LCOH (EUR/MWh)	42.1	44.6	44.6
○ Initial Reservoir Temperature (°C)	55.2	55.2	55.2
○ Average Reservoir Heat Extraction (MWth)	3.42	3.41	3.41
○ Average Production Well Temperature Drop (°C)	2.0	2.1	2.2
○ Average Injection Well Pump Pressure Drop (kPa)	-36.5	-58.8	-99.2

	(-3.72 m H2O)	(-5.99 m H2O)	(-10.11 m H2O)
○ Average Production Well Pump Pressure Drop (kPa)	477.1 (48.6 m H2O)	456.5 (46.53 m H2O)	419.5 (42.77 m H2O)
○ Average Annual Heat Production (GWh)	27.00	26.93	26.89
○ Average Pumping Power (Mwe)	0.01	0.01	0.01
○ Thermal drawdown (°C)	1.0217	1.0204	1.0220
Capital and O&M Costs			
○ **Total Capital Cost (M€)**	**11.87**	**10.56**	**10.55**
○ Wellfield Cost (M€)	5.36	6.70	6.70
○ Surface Plant Cost (M€)	1.01	1.52	1.52
○ Exploration Cost (M€)	3.15	0.00	0.00
○ Field Gathering System Cost (M€)	0.95	0.95	0.95
○ Stimulation Cost (M€)	1.38	1.38	1.38
○ **Total O&M Cost (M€/year)**	**0.33**	**0.35**	**0.35**
○ Wellfield O&M Cost (M€/year)	0.12	0.14	0.14
○ Surface Plant O&M Cost (M€/year)	0.19	0.20	0.20
○ Make-Up Water O&M Cost (M€/year)	0.00	0.00	0.00
○ Average annual pumping costs (M€/year)	0.01	0.01	0.01

Key Findings

One of the central observations concerns the Levelised Cost of Heat (LCOH) across the three simulation runs. The LCOH increased from 42.1 EUR/MWh in the first scenario to 44.6 EUR/MWh in both the second and third runs. This rise in LCOH can be directly linked to a reduction in the assumed plant lifetime, from 50 years in Run 1 to 25 years in Runs 2 and 3. Shorter operational periods result in higher annualised costs, as capital investments must be recovered over a shorter timeframe.

With respect to the average injection well pump pressure drop, the results showed a progressive increase: from -36.5 kPa (equivalent to 3.72 metres of water column) in the first run, to -58.8 kPa (5.99 metres H_2O) in the second run, and reaching -99.2 kPa (10.11 metres H_2O) in the third run. This trend suggests a growing resistance in the injection well system as the simulations progressed. However, it is important to note that a larger well diameter is generally expected to improve fluid flow and typically result in lower injection pressures; the observed increase here could be influenced by other operational or geological factors included in the scenarios.

In contrast, the average production well pump pressure drop exhibited a decreasing pattern. It declined from 477.1 kPa (48.6 metres H_2O) in the first simulation, to 456.5 kPa (46.53 metres H_2O) in the second, and further down to 419.5 kPa (42.77 metres H_2O) in the third run. This reduction indicates an enhancement in the performance of the production well, which can likely be attributed to the use of a larger production well diameter, progressing from 6 1/4 inches in the initial run to 8 inches in the third scenario. This design change has a favourable effect on reducing flow resistance and optimising well output.

Taken together, these findings highlight the interplay between operational assumptions, design modifications, and system performance in geothermal project simulations. The results underline the importance of carefully considering how plant lifetime, well configuration, and fluid dynamics collectively shape both economic and technical outcomes.

Other Observations

1. Heat Production:
   - The Average Net Heat Production remained relatively stable (3.08 MWth in Run 1, 3.07 MWth in Runs 2 and 3).
   - The Average Annual Heat Production slightly decreased from 27.00 GWh in Run 1 to 26.89 GWh in Run 3, indicating marginal efficiency losses.
2. Capital Costs:
   - The Total Capital Cost decreased from 11.87 M€ (Run 1) to 10.55 M€ (Run 3), mainly due to the removal of exploration costs in Runs 2 and 3.
   - However, the Wellfield Cost increased in Runs 2 and 3, likely due to changes in well diameters.
3. Operational Costs:
   - Total O&M Costs increased from 0.33 M€/year in Run 1 to 0.35 M€/year in Runs 2 and 3, likely due to higher wellfield operational expenses.

Conclusions

The first scenario produced the lowest LCOH. However, this outcome was accompanied by a higher overall capital cost, primarily driven by substantial exploration expenses. The low LCOH in this case can be attributed to the assumption of a lengthy plant lifetime of 50 years, which helps to spread fixed costs over a longer operational period, thus reducing the average cost per unit of heat produced.

The third simulation, by contrast, resulted in the lowest production well pressure drop of all the scenarios. However, this advantage was offset by the highest injection well pressure drop observed among the tests. This indicates a shift in the pressure dynamics within the geothermal system, where improvements in one aspect can lead to increased challenges elsewhere.

It was observed that the technical modifications implemented in Runs 2 and 3, particularly the use of larger well diameters, contributed to a significant reduction in production well pressure drop. Nevertheless, these design changes also led to a corresponding increase in injection well pressure drop, highlighting the inherent trade-off between well performance and system design.

These results underscore the importance of balancing capital expenditure, well configuration, and operational efficiency when selecting the optimal scenario for geothermal energy development. Decision-makers should consider how adjustments to one parameter, such as well diameter, may influence both costs and system behaviour in other areas.

Overall, the outputs from all simulations remained within a close range of the expected thermodynamic and economic values, providing confidence in the model's suitability for scenario analysis and early-stage geothermal planning.

Testing of the Cornwall Case Study (United Kingdom)

The Cornwall case study is centred on the potential for geothermal heat use as an additional product from the United Downs geothermal power plant in Cornwall, UK.

Development at United Downs to date includes:

- The drilling of a geothermal doublet into a fractured granite geothermal reservoir:
    - 5.2 km measured depth production well and 2.7 km measured depth injection well, both drilled into the subvertical Porthtowan Fault Zone
- The construction of a binary cycle ORC power plant
- the construction of a 100 tonne-per-annum lithium extraction plant.

Post-power production, there is scope for the utilisation of excess heat available within the geothermal waters prior to reinjection into the subsurface. Currently, there is no development for the use of excess heat at United Downs for district heating (or other heat usage). Despite this, there remains scope to do so, and this case study remains an early-stage heat development.

The SAPHEA GEOHPIRES calculation module, built into the online SAPHEA toolbox, was used to assess the heat potential. Geological, technical and financial data collected during geological exploration, drilling and testing and other later developments were input into the model. Data collected during drilling and logging of the geothermal wells is vital due to limited subsurface data availability in the region (subsurface mine workings to 800 m depth, three deep wells approximately 2 km deep drilled during the Hot Dry Rocks Project and one 5 km deep well drilled at the Eden Project into a different granite body).

Currently, the United Downs plant is undergoing commissioning; therefore, no long-term production data has been collected. Assumptions have been made on aspects of the heating system due to the lack of a planned heating project (providing a level of heat requirements, etc.). It is highlighted below where this is the case.

Table 8: User inputs used for the Cornwall case study.

Parameters	**1st Run** Modelling total heat available with no power generation *Simulation Date 2025-06-23*	**2nd Run** Effect of flow rate increase on Run 1 results *Simulation Date 2025-06-23*
Reservoir Depth	5 km	5 km
Gradient	33 °C/km	33 °C/km
Number of Production Wells	1	1
Number of Injection Wells	1	1
Thickness	5 km	5 km
Production Flow Rate per Well	30 kg/s	40 kg/s

Injection Temperature	60 °C	60 °C
Productivity Index	2 kg/sec/bar	2 kg/sec/bar
Injectivity Index	2 kg/sec/bar	2 kg/sec/bar
Surface Temperature	15 °C	15 °C
End-Use Efficiency Factor	0.9	0.9
Utilisation Factor	0.98	0.98
Plant Lifetime	30	30
EUR to USD Exchange Rate	1.09	1.09
Discount Rate	0.04	0.04
Cost Adjustment Factors: ○ Reservoir Stimulation Capital Cost (unit: M€/year) ○ Surface Plant Capital Cost (unit: M€/year) ○ Field Gathering System Capital Cost (unit: M€/year) ○ Exploration Capital Cost (unit: M€/year) ○ Wellfield O&M Cost (unit: M€/year) ○ Surface Plant O&M Cost (unit: M€/year)	1 1 1 1 1	1 1 1 1 1

Table 9: Model results received for the Cornwall case study.

Results	**1st Run** Modelling total heat available with no power generation *Simulation Date 2025-06-23*	**2nd Run** Effect of flow rate increase on Run 1 results *Simulation Date 2025-06-23*
Average direct-use heat production capacity (MW_th)	12.57	17.13
Average annual heat production (GWh/yr)	107.91	147.03
Average production temperature (°C)	170.04	172.45
LCOH (EUR/MWh_th)	15.95	13.59
Drilling and completion costs (MEUR)	19.58	19.58
Drilling and completion costs per well (MEUR)	9.79	9.79
Stimulation costs (MEUR)	1.38	1.38
Surface power plant costs (MEUR)	4.16	5.66
Field gathering system costs (MEUR)	0.88	.97
Total surface equipment costs (MEUR)	5.04	6.63
Exploration costs (MEUR)	8.39	8.39

Total capital costs (MEUR)	34.39	35.98
Wellfield O&M costs (MEUR/yr)	0.28	0.33
Surface plant O&M costs (MEUR/yr)	0.29	0.45
Make-Up water O&M costs (MEUR/yr)	0	0
Average annual pumping costs (MEUR/yr)	0	0.02
Total operating and maintenance costs (MEUR/yr)	0.58	.8
Bottom-hole temperature (°C)	170	170
Average production well temperature drop (°C)	9.96	7.55
Average pumping power (MW_e)	0	0.02
Plant outlet pressure (kPa)	1 062.7	1062.72
Production wellhead pressure (kPa)	1 131.67	1131.67
Average injection well pump pressure drop	-121.44	477.55
Average production well pump pressure drop	-719.79	-144.18

Key Findings

One of the main observations from the modelling results is that the LCOH in EUR/MWh shows a clear trend of decreasing as the production flow rate increases. This indicates that, all other factors being equal, higher flow rates can help improve the economic viability of the geothermal system by distributing fixed costs over a greater amount of generated heat.

In terms of operational parameters, the model revealed that the average injection well pump pressure drop (measured in kilopascals) initially yielded negative values. However, as the flow rate was increased, this pressure drop shifted to positive values and continued to rise with further increases in flow. This behaviour suggests that the system dynamics become more realistic and physically plausible at higher flow rates, possibly due to overcoming initial limitations or assumptions in the model setup.

Similarly, the average production well pump pressure drop also started with negative values during initial simulations. As with the injection side, increasing the flow rate resulted in higher, positive pressure drops. This pattern underscores the importance of proper parameter selection in the early stages of model configuration and highlights the sensitivity of pressure-related outputs to changes in operational flow rates.

Overall, these findings emphasize the interconnectedness of economic and technical parameters in geothermal project planning, and they point to the need for careful calibration when interpreting pressure results at different flow scenarios.

Conclusions

Overall, the scenario analysis conducted for the Cornwall (United Downs) site is constrained by the current limitations in available data. The absence of direct production data from United Downs means that certain assumptions had to be made in the modelling process. As more empirical data becomes available—particularly actual production figures—the model can be further refined to increase its accuracy and relevance.

It should also be noted that the current modelling approach assumes utilisation of the entire thermal potential of the United Downs geothermal resource. In practice, however, heat extraction would likely be a byproduct of power generation, not the primary purpose. This distinction means that the modelled scenario represents a theoretical maximum, and further work will be required to adapt the tool for more realistic, integrated heat and power applications as operational experience grows.

Despite these limitations, the application of the GEOPHIRES model to the United Downs case has produced a valuable initial set of results. These outcomes serve as a solid foundation for ongoing assessment and can be progressively refined as new data and operational insights become available. As the project evolves, the model will continue to be an important decision support resource for future planning and optimisation efforts.

Testing of the Vienna Case Study (Austria)

The final testing of the SAPHEA GEOPHIRES CM has been completed for the case study in the Vienna Basin, specifically focusing on geothermal reservoir conditions comparable to the Aderklaa conglomerates (one of the main geological reservoirs of the Vienna Basin). This reservoir is currently being drilled by OMV and Wien Energy through the DEEEP project and will allow us to have a point of comparison for the tool results.

The objective of this testing is to assess the accuracy and suitability of the tool for modelling geothermal resources in conditions analogous to the actual geological and operational parameters found in the Vienna Basin. Two distinct test scenarios were modelled to assess the effectiveness of the calculation module.

TEST 1	
INPUTS	**VALUE**
Reservoir Depth	3 km
Gradient	30 degC/km
Number of Production Wells	1
Number of Injection Wells	1
Production Flow Rate per Well	40 kg/s
Injection Temperature	75 degC
BASIC INPUTS	**VALUE**
Productivity Index	11 kg/s/bar
Injectivity Index	11 kg/s/bar
Surface Temperature	12 degC
End-Use Efficiency Factor	0.9
Utilization Factor	0.6
Plant Lifetime	30 years
EUR to USD Exchange Rate	1.08
Discount Rate	0.07
ADVANCED INPUTS	**VALUE**
Well Drilling and Completion Capital Cost Adjustment Factor	1.2
Reservoir Stimulation Capital Cost Adjustment Factor	1.1
Surface Plant Capital Cost Adjustment Factor	1
Field Gathering System Capital Cost Adjustment Factor	1

Exploration Capital Cost Adjustment Factor	1.3
Wellfield O&M Cost Adjustment Factor	1.2
Surface Plant O&M Cost Adjustment Factor	1
Water Cost Adjustment Factor	0.9
Electricity Rate	0.15
OUTPUTS	**VALUE**
Average direct-use heat production capacity	3.68 MW_th
Average annual heat production	19.37 GWh/yr
Average production temperature	99.35 deg.C
LCOH	116.26 EUR/MWh_th
Drilling and completion costs	12.19 MEUR
Drilling and completion costs per well	6.1 MEUR
Stimulation costs	1.54 MEUR
Surface power plant costs	1.23 MEUR
Field gathering system costs	1.08 MEUR
Total surface equipment costs	2.31 MEUR
Exploration costs	7.38 MEUR
Total capital costs	23.43 MEUR
Wellfield O&M costs	0.23 MEUR/yr
Surface plant O&M costs	0.2 MEUR/yr
Make-up water O&M costs	0 MEUR/yr
Average annual pumping costs	0.05 MEUR/yr
Total operating and maintenance costs	0.48 MEUR/yr
Bottom-hole temperature	102 deg.C
Average production well temperature drop	2.65 deg.C
Average pumping power	0.06 MW_e
Plant outlet pressure	385.02 kPa
Production wellhead pressure	453.97 kPa
Average injection well pump pressure drop	444.3 kPa
Average production well pump pressure drop	822.86 kPa

Test 1 involved inputs such as a reservoir depth of 3 km, a geothermal gradient of 30°C/km, a production flow rate per well of 40 kg/s, an injection temperature of 75°C, and a drilling cost adjustment factor of 1.2.

TEST 2	
INPUTS	**VALUE**
Reservoir Depth	3 km
Gradient	30 degC/km
Number of Production Wells	1
Number of Injection Wells	1
Production Flow Rate per Well	80 kg/s
Injection Temperature	50 degC
BASIC INPUTS	**VALUE**
Productivity Index	11 kg/s/bar
Injectivity Index	11 kg/s/bar

Surface Temperature	12 degC
End-Use Efficiency Factor	0.9
Utilization Factor	0.6
Plant Lifetime	30 years
EUR to USD Exchange Rate	1.08
Discount Rate	0.07
ADVANCED INPUTS	**VALUE**
Well Drilling and Completion Capital Cost Adjustment Factor	2
Reservoir Stimulation Capital Cost Adjustment Factor	1.1
Surface Plant Capital Cost Adjustment Factor	1
Field Gathering System Capital Cost Adjustment Factor	1
Exploration Capital Cost Adjustment Factor	1.3
Wellfield O&M Cost Adjustment Factor	1.2
Surface Plant O&M Cost Adjustment Factor	1
Water Cost Adjustment Factor	0.9
Electricity Rate	0.15
OUTPUTS	**VALUE**
Average direct-use heat production capacity	15.28 MW_th
Average annual heat production	80.33 GWh/yr
Average production temperature	100.66 deg.C
LCOH	49.67 EUR/MWh_th
Drilling and completion costs	20.32 MEUR
Drilling and completion costs per well	10.16 MEUR
Stimulation costs	1.54 MEUR
Surface power plant costs	5.08 MEUR
Field gathering system costs	1.34 MEUR
Total surface equipment costs	6.41 MEUR
Exploration costs	11.27 MEUR
Total capital costs	39.54 MEUR
Wellfield O&M costs	0.39 MEUR/yr
Surface plant O&M costs	0.4 MEUR/yr
Make-Up water O&M costs	0 MEUR/yr
Average annual pumping costs	0.23 MEUR/yr
Total operating and maintenance costs	1.01 MEUR/yr
Bottom-hole temperature	102 deg.C
Average production well temperature drop	1.34 deg.C
Average pumping power	0.31 MW_e
Plant outlet pressure	385.02 kPa
Production wellhead pressure	453.97 kPa
Average injection well pump pressure drop	908.71 kPa
Average production well pump pressure drop	2 249.87 kPa

Test 2 utilised a higher production flow rate of 80 kg/s, a lower injection temperature of 50°C, and a higher drilling cost adjustment factor of 2, reflecting conditions more closely aligned with realistic operational parameters and economic considerations of the Austrian geothermal market.

Both tests shared common inputs, including identical reservoir depths, geothermal gradients, productivity and injectivity indices, surface temperatures, efficiency and utilisation factors, project lifetimes, currency exchange rates, and discount rates.

Key Findings

Upon comparative evaluation, Test 2 provided more coherent and realistic outcomes, consistent with observed parameters and recent exploration activities in the Vienna Basin, notably within the Aderklaa conglomerates targeted by OMV and Wien Energy's DEEEP initiative. The increased production rate (80 kg/s) and lower injection temperature (50°C) in Test 2 more accurately reflected the physical and operational constraints typical of geothermal reservoirs in the Vienna Basin.

These parameters yielded more realistic economic and technical assessments, validating the tool's applicability and reliability in simulating geothermal reservoir conditions specific to the Vienna Basin.

Conclusions

The application of the SAPHEA GEOPHIRES CM to the Vienna Basin has demonstrated that the tool is both accurate and reliable for this geological setting. Throughout the testing process, the CM produced results that were consistent with expectations and in line with established benchmarks for the region. This level of accuracy became particularly apparent when the model was configured using realistic operational parameters, as illustrated in the second test scenario. By carefully aligning the input data with the actual conditions of the Vienna Basin, the tool was able to simulate system performance with a high degree of confidence.

Based on these findings, the SAPHEA GEOPHIRES CM is considered validated for use in future feasibility studies and geothermal resource assessments conducted within the geological context of the Vienna Basin. Its robust performance suggests that it can be trusted as a decision support tool for planners and engineers working on new projects in the area.

Importantly, the model is especially suitable for application to reservoirs that are similar to the currently explored Aderklaa conglomerates. This further highlights its value for stakeholders involved in ongoing and prospective geothermal developments in the Vienna Basin and comparable settings.

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