Interreg CENTRAL EUROPE
Co-funded by the European Union

TRANSGEO

Proof-of-concept study on reuse of abandoned wells for BTES Development

TRANSGEO Deliverable 1.1.4

Version 1
04 2026

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The TRANSGEO project (https://www.interreg-central.eu/projects/transgeo/) is co-funded by the European Regional Development Fund through the Interreg Central Europe program. The overall objective of TRANSGEO is to investigate the potential to transform abandoned hydrocarbon wells into new sources of green geothermal energy. To reach this goal, the TRANSGEO team is providing new tools and knowledge to support communities and industries in the energy transition and to break down economic and technical barriers to well reuse.

The report reflects the views of the authors.

A. Description of BTES technology

Borehole Thermal Energy Storage (BTES) is a seasonal thermal energy storage technology that utilizes the subsurface as a medium for storing heat or cold over extended periods. The fundamental operating principle involves transferring thermal energy to, or from, the surrounding geological formation through borehole heat exchangers (BHEs), which are closed-loop systems where a heat carrier fluid circulates without direct contact with the subsurface materials. During the charging phase, excess thermal energy, which can be sourced from industrial processes, cogeneration plants, electricity from renewable electricity systems surplus, surplus heat from solar thermal arrays, or waste heat from cooling systems, is injected into the ground, elevating the temperature of the rock mass surrounding the wells. During the heat extraction phase, typically corresponding to periods of winter heating demand, this stored thermal energy is extracted and delivered to end users. The physical mechanism governing BTES operation is primarily heat conduction, although convective processes may contribute in fractured or permeable formations with groundwater movement.

While BTES is a well-established technology in shallow geothermal applications, typically ranging from 20 to 200 meters in depth, its implementation at depths exceeding 500 meters represents an emerging solution in geothermal engineering. Shallow BTES systems have been successfully deployed for decades, with notable examples including the high-temperature storages in Luleå (Sweden), Emmaboda (Sweden), and Neckarsulm (Germany). These systems typically utilize fields of dozens to hundreds of boreholes with U-tube or coaxial collectors, achieving storage volumes of up to several hundred thousand cubic meters. Reported design and operating parameters span a wide range: borehole numbers of approximately 120 (Luleå, 65 m deep, ~120 000 m^3), 140 (Emmaboda, 150 m deep, ~323 000 m^3) and 528 (Neckarsulm, 30 m deep, ~63 000 m^3); charging temperatures from solar or waste-heat sources of 60–85 °C, with maximum stored rock-mass temperatures of 45–65 °C; and annual injected energies of the order of 1–4 GWh per system, of which typically 30–50 % is recovered during the heating season (Nordell, 1994; Heidemann et al., 2003; Nordell et al., 2015; Reuss, 2015).

The extension of BTES to greater depths, termed either medium-deep BTES (MD-BTES) at 500-1000 m or deep BTES at depth >1000 m, offers several advantages. First, deeper installations access higher temperatures due to the geothermal gradient, allowing higher storage temperatures, reducing the temperature lift required from heat pumps in the case of shallow wells during extraction and improving overall system efficiency (or enhancing utilization of heat pumps opposed to shallow application). Second, in the case of deeper storage there is reduced thermal interference with shallow aquifers and surface ecosystems, addressing regulatory concerns associated with temperature change in drinking water resources. Third, deeper boreholes require less surface land area per unit storage volume, a critical consideration in urban or industrial settings where land availability is constrained. However, deep BTES also presents unique technical challenges. The hydraulic resistance of long flow paths requires careful design to avoid excessive parasitic power consumption by circulation pumps. Thermal short-circuiting between descending and ascending fluid in annulus and tubing becomes more pronounced with increasing depth, requiring well isolated tubing such as vacuum insulated tubing. Furthermore, the capital costs associated with deep drilling are substantial, making the repurposing of existing hydrocarbon wells particularly attractive especially when used for thermal storage.

Deep BTES systems always involve coaxial borehole heat exchanger configurations rather than the U-tube designs, which are common in shallow applications. Several technical considerations are the reason for this preference. Most importantly, at depths exceeding 500 meters, the hydraulic resistance associated with U-tube geometries becomes very high, leading to high pressure drops and correspondingly high circulation pump energy consumption. Comparatively, coaxial configuration offers larger flow cross-sections and more favorable hydraulic characteristics for a given borehole diameter at larger depths.

The most effective coaxial design for BTES applications is the annular inflow configuration (CXA), where the colder working fluid descends through the outer annulus (thereby is in direct thermal contact with the formation) and heated working fluid ascends through a centrally positioned, well-insulated inner pipe or tubing. This arrangement maximizes heat exchange during the downward path (injection) while minimizing thermal losses during the return (production), which is particularly critical in the cooler upper sections of the well where the temperature differential between ascending fluid and the surrounding rock is highest.

The thermal performance of a deep coaxial BHE (DCBHE) is governed by the heat transfer processes occurring in three domains: convective heat transfer between the working fluid and the pipe walls, conductive heat transfer through the pipe materials and any gas insulating layers, and conductive heat transfer into the surrounding geological formation. Thermal radiation between surfaces becomes significant only at high temperature differences and when surfaces are vacuum gapped. In a typical coaxial DBHE, the annular space between the inner (insulated) tubing and the outer casing is filled with circulating fluid (water or brine). Liquids are largely opaque to infrared radiation, so radiative heat transfer through the fluid is effectively zero, so in this part of heat exchange zone conduction and convection in the fluid completely dominate. The one scenario where radiation cannot be completely neglected is if part of the wellbore has a dry, vacuum-filled space to reduce thermal short-circuiting between the hot upward flowing fluid and the cooler downward flowing fluid. At the temperatures typical of DBHEs of 60–150 °C, radiative heat transfer across a narrow annular gap is small compared to natural convection in the gas. It only starts becoming non-trivial at temperatures above roughly 200–300 °C, which would apply to very deep geothermal wells of at least 5-6 km in Pannonian Basin, for example.

Optimization of the system involves minimizing the total resistance during heat extraction while maximizing it during heat storage to retain thermal energy. Water is the preferred working fluid for deep BTES applications due to its favorable thermophysical properties, including high specific heat capacity, low viscosity, and minimal cost. The volumetric heat capacity of water significantly exceeds that of most alternative fluids, enabling greater heat transport per unit volume circulated.
The successful deployment of medium and deep BTES requires careful integration with existing or planned heating infrastructure. Figure 1 illustrates the conceptual integration scheme, where the BTES system is coupled with a district heating network and one or more sources of surplus heat. During winter months, when heating demand peaks, the BTES discharges stored heat to supplement direct geothermal production. During summer months, when heating demand is minimal but waste heat availability may be high, the system operates in charging mode, injecting thermal energy into the reservoir.

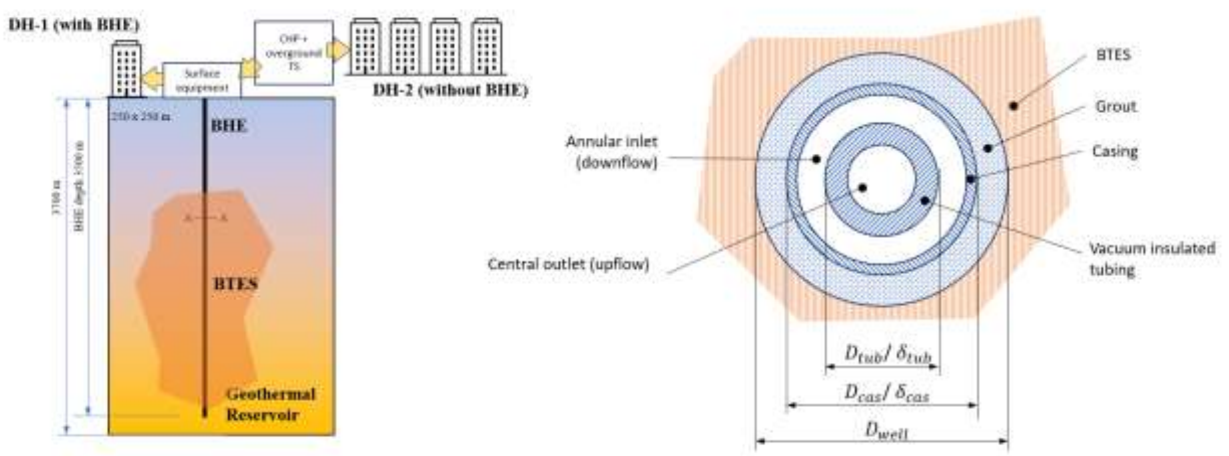

Figure 1. The conceptual scheme of the simulation problem (left) and cross-section of the borehole heat exchanger with annular inlet BHE-CXA (right).

The surface equipment required for such integration typically includes multiple heat exchangers to manage the temperature interfaces between different fluid circuits, control valves to regulate flow distribution, and possibly high-temperature heat pumps to elevate the temperature of extracted heat to levels suitable for district heating networks or other direct heating applications. The control logic governing valve positions and flow rates must balance competing objectives: maximizing direct geothermal contribution during discharge, maximizing heat injection during charge, and minimizing parasitic electrical consumption from pumps and heat pumps.

For fourth-generation district heating systems, which operate at supply temperatures of 60-70°C, the integration of deep BTES is particularly attractive. The baseline temperatures achievable at depths of 1-2 km, typically ranging from 40-80°C depending on geothermal gradient, can often provide direct heating without heat pump assistance during the early stages of the discharge cycle. As the storage temperature declines over the heating season, heat pumps can provide the necessary temperature lift to maintain supply conditions.

B. Lessons learned

Through different modelling parameters of Savica-1 well, sensitivity analysis conducted in BTES modelling revealed that thermal recovery in deep BTES systems is most strongly influenced by a limited set of parameters.

B.1. Modelling Parameter Findings

The undisturbed geothermal gradient emerged as the most influential geological parameter, determining the baseline temperature regime within which storage operates. Higher gradients provide warmer initial conditions, reducing temperature losses during storage and improving extraction temperatures.

Flow rate during both charge and discharge phases proved highly influential, reflecting the fundamental trade-off between heat transfer rate and residence time. Higher flow rates increase the rate of heat exchange but reduce the temperature at the BHE outlet, while lower flow rates achieve greater temperature changes but at reduced power levels. The optimal flow rate depends on the specific objectives of the system, maximizing instantaneous temperature versus maximizing stored heat recovery—and must be determined through site-specific analysis. Furthermore, circulation pumps are one of the largest consumers of electricity in the system, making it a great share of OPEX. Through analysis of SPF (Seasonal Performance Factor), the ratio of extracted heat should be much higher than the consumed electricity, presumably above 15.

Inlet temperatures during both injection and extraction phases were also identified as key parameters. Higher charging temperatures increase the thermal gradient driving heat injection, accelerating the storage process and achieving higher stored energy densities. Higher extraction inlet temperatures (i.e., the temperature at which fluid returns to the BHE after passing through the heat user's system) reduce the temperature differential driving heat extraction, lowering power output but potentially improving long-term storage efficiency.

Crucially, the sensitivity analysis demonstrated that most of the influential parameters are operational rather than fixed geological or well design parameters. This finding has profound implications for project development: deep BTES systems can be optimized through careful engineering and adaptive control strategies rather than being limited by predetermined site conditions. Operational flexibility enables system operators to respond to changing conditions, balance competing objectives, and maximize economic returns.

B.2. Environmental Impact Findings

Studying impact of BTES systems from an ecological standpoint, life cycle assessment (LCA) studies of medium-deep BTES systems have quantified their environmental performance relative to conventional heating alternatives (Lanahan & Tabares-Velasco, 2017; Welsch et al., 2016). The LCA approach captures environmental burdens across all phases of the system lifecycle, including material extraction and manufacturing, construction and installation, operation and maintenance, and end-of-life decommissioning. For deep BTES systems, the construction phase, particularly drilling and BHE installation dominates the upfront environmental footprint. However, these impacts are substantially reduced when repurposing existing wells, as the drilling phase is eliminated. During operation, BTES systems demonstrate minimal environmental impact. As closed-loop systems, they produce no fluid emissions, consume negligible water, and generate no noise beyond that associated with circulation pumps. The greenhouse gas emissions associated with operation are limited to the indirect emissions from electricity consumption for pumps and heat pumps, which can be minimized through renewable electricity sourcing. Comparative analyses indicate that BTES systems integrated with district heating networks can achieve substantial greenhouse gas emission reductions relative to fossil fuel alternatives. The magnitude of reduction depends on the carbon intensity of displaced heating fuels, the carbon intensity of electricity used for system operation, and the storage efficiency achieved. Systems charged with waste heat that would otherwise be rejected to the environment achieve particularly favorable emission reduction metrics, as the heat input carries no associated carbon burden.

B.3. Economic and Regulatory Lessons

The TRANSGEO pilot studies, including the Savica-1 BTES site in Croatia, have yielded important economic and regulatory insights. Economic viability depends critically on the proximity of both heat source and heat consumer. Short transport distances, typically measured in hundreds of meters rather than kilometers, are essential for economic viability, as pipeline capital costs scale linearly with distance and heat losses increase with longer transmission distances.

The regulatory landscape for well repurposing remains fragmented across European jurisdictions. Existing mining and hydrocarbon legislation in many countries does not clearly address the transfer of long-term liability for repurposed wells, creating uncertainty for project developers and investors. Land-use planning restrictions often conflict with small-scale geothermal installations at legacy well sites, particularly when wells are located in rural or environmentally sensitive areas. These non-technical barriers can outweigh technical risks and delay or prevent otherwise viable projects.

However, a key advantage for closed-loop BTES systems is their favorable regulatory treatment in some jurisdictions. Because BTES systems do not involve permanent abstraction of geothermal fluids, they may not be subject to the same concession fees and exploitation regimes applicable to open-loop hydrothermal systems. This can significantly improve project economics, particularly in countries where geothermal resource fees are substantial.

C. Requirements to reuse hydrocarbon wells as BTES with Deep Borehole Heat Exchangers

The screening criteria for hydrocarbon wells suitable for repurposing as deep BTES systems can be categorized into four groups: 1. initial well properties (fixed), 2. geological conditions (fixed), 3. well design parameters (optimizable), and 4. operational properties (optimizable). Understanding which parameters are fixed by existing conditions and which can be modified through engineering design is essential for efficient project development.

C.1. Existing Well Properties (Fixed Parameters)

Well location: The geographic location of the well relative to heat sources and sinks is perhaps the most critical feasibility determinant. Excessive distance to heat consumers leads to prohibitive pipeline costs and thermal losses during transmission. Similarly, distance to waste heat sources, such as industrial facilities, power plants, or data centers, determines the cost and practicality of capturing surplus heat for storage. General guidelines suggest that distances should not exceed 3 km, with shorter distances strongly preferred.

Casing size and condition: The internal diameter of the well casing at depth fundamentally constrains the BHE design. Wells with casing diameters of 7 inches (177.8 mm) or larger at the target depth are considered most suitable for repurposing. Smaller diameters may still be usable but impose limitations on flow rates and may preclude the installation of adequately insulated inner pipes. This is especially constrained on some oil producing wells where liners of 5 1/2" could often be found. The condition of the casing including corrosion, deformation, or cement bond quality must be assessed through logging and pressure testing to ensure mechanical integrity for decades of operational service.

Well depth: Minimum depth requirements depend on the intended application and is directly linked to the local geothermal gradient. For BTES applications, greater depth provides larger storage volume per well and access to higher ambient temperatures. Areas with geothermal gradient above 45°C/km could especially be marked for deep BHE revitalization success, but deep BTES could be successful even at some lower gradients, as more heat could be stored and extracted, but often with utilization of heat pumps. Deeper wells (>2000 m) offer enhanced storage capacity and potentially enable direct heating applications without heat pump assistance.

Well status and accessibility: Temporarily abandoned wells, or more commonly called shut-in wells, those that are no longer producing but retain casing integrity and surface access, are preferable candidates for repurposing. Fully plugged and abandoned wells, in which cement plugs have been set at multiple depths and casing has been cut below ground level, require substantially more intervention to re-establish access and may not be economically viable for repurposing due to high capital expenses. This is not only due to well revitalization expenses, but also complete reconstruction of the drill site, which can sometimes be a significant part of the overall capital expenses.

C.2. Geological Conditions and Reservoir Properties (Fixed Parameters)

Geothermal gradient: The undisturbed geothermal gradient is the primary geological control on BTES performance. Higher gradients provide higher baseline temperatures, reducing the temperature lift required from heat pumps during extraction and improving overall system efficiency. Gradients of 30-50°C/km are considered favorable, while gradients exceeding 50°C/km are exceptional and enable premium performance. However, BTES systems could work even on lower gradients, but this mostly requires the use of heat pumps.

Thermal properties of rock: The volumetric heat capacity of the rock formation determines the thermal energy that can be stored per unit volume. Higher heat capacity is always preferable (rocks with higher porosity saturated with water but with lower permeability), as it enables more compact storage for a given energy capacity. The role of thermal conductivity is more nuanced: higher conductivity facilitates faster charging and discharging but also accelerates heat losses to surrounding formations during storage periods. Medium thermal conductivities (2-3 W/m·K) are often considered optimal for BTES applications, balancing charge/discharge rates against storage retention.

Hydrogeological conditions: Locations with groundwater flow through or around the storage volume should be avoided to prevent advective heat loss where unconfined thick aquifers exist. Even modest groundwater velocities can transport stored heat away from the borehole vicinity, dramatically reducing storage efficiency. Formations with low hydraulic conductivity—such as tight clays, unfractured crystalline rocks, or low-permeability sedimentary units—are therefore preferred for BTES applications. Where some permeability exists, detailed hydrogeological characterization is essential to quantify potential heat losses and inform system design.

Formation thickness and homogeneity: The thickness of the storage formation influences the vertical distribution of stored heat and the potential for thermal stratification. Homogeneous formations with consistent thermal properties simplify design and modelling, while heterogeneous formations with interbedded low-conductivity layers may enhance thermal retention by impeding vertical heat flow.

C.3. Well Design Parameters (Optimizable)

DBHE configuration: Coaxial configuration with annular inflow (CXA) is the established standard for deep BTES applications. This configuration maximizes thermal contact with the formation during the downward flow path while insulating the upward return flow. Alternative configurations, such as centered inflow (fluid descending through the inner pipe and ascending through the annulus - CXC), have been shown to be less efficient for heating applications due to greater thermal losses from the ascending fluid to the surrounding rock mass.

Inner pipe insulation: The thermal conductivity of the inner pipe material is a critical design parameter. Standard steel tubing (thermal conductivity circa 50 W/m·K) provides minimal insulation, allowing substantial heat transfer from the warm ascending fluid to the cooler descending fluid, i.e. thermal short-circuiting. High-density polyethylene or polybutylene (HDPE/PB) liners (thermal conductivity ~0,4 W/m·K) offer improved performance at moderate cost, but are not suitable for larger depths due to material properties and temperature restrictions. Vacuum-insulated tubing (VIT), with thermal conductivities as low as 0,01-0,03 W/m·K, provides the highest level of insulation but at substantially greater cost. The optimal choice depends on the specific project parameters, namely depth, balancing improved thermal performance against incremental capital cost.

Outer pipe and cementation: The casing functions as the outer pipe in a coaxial DBHE system. Its thermal conductivity is high and it facilitates good heat exchange with the formation, which is satisfied by standard steel casing inserted in deep hydrocarbon wells. The cement behind the casing should also have high thermal conductivity to minimize thermal resistance between the casing and formation. Standard oilfield cements are less than optimal, enhanced cements with thermal conductivities of >2,2 W/m·K can substantially improve system performance, but this is not a norm when drilling hydrocarbon wells.

Working fluid selection: Water is the preferred working fluid for most applications. Where freeze protection is required, glycol additives may be incorporated with careful consideration of their impacts on thermophysical properties and pumping power requirements. The selection of working fluid should also consider corrosion compatibility with well materials and environmental regulations.

C.4. Operational Properties and Control Strategies (Optimizable)

Flow rate optimization: The mass flow rate of circulating fluid is a key operational control variable. For a given well geometry and thermal regime, there exists an optimal flow rate that balances competing objectives. Higher flow rates increase total heat exchange and increase pumping power consumption. Lower flow rates achieve lower pump consumption, but with reduced thermal power levels and higher inlet/outlet temperature difference. The optimal flow rate depends on the specific heating objective and may vary seasonally as the system transitions between charge and discharge modes.This is especially visible during controlling flow from the aspect of temperature at the wellhead; i.e. high flow rates leads to lower temperature at the wellhead and higher power, while low flow rates leads to higher temperature at the wellhead but lower power, as surface heating system inlet/outlet temperature defines acceptable temperature.

Inlet temperature management: The temperature at which fluid enters the DBHE pipe during both charge and discharge phases significantly influences system performance. During charging, higher inlet temperatures increase the thermal gradient driving heat injection, enabling more rapid storage. During discharge, the inlet temperature is determined by the heat user's return temperature, which may be outside the operator's direct control. Where possible, designing the connected heating system for low return temperatures improves extraction performance by maintaining a larger temperature differential between the fluid and the formation.

Seasonal operating schedule: The duration and timing of charge and discharge phases must be matched to the availability of surplus heat and the pattern of heating demand. Numerical simulations indicate that a six-month charge phase followed by six-month discharge represents a typical seasonal cycle in temperate climates. However, the optimal schedule may vary with local climate, heat source characteristics, and system design.

Control system logic: Advanced control systems capable of optimizing valve positions, flow rates, and heat pump operation in real time can substantially improve system performance. Model predictive control approaches, which use system models to forecast future conditions and optimize current actions, are particularly promising for BTES applications where thermal dynamics are slow and seasonal patterns are predictable.

C.5. Comprehensive Parameter Screening Matrix

Table 1: Parameter screening matrix for deep BTES well repurposing.

Parameter category	Parameter	Typical range	Optimal value	Impact	Variability
Initial well properties	Well depth	500-3000 m	>2000 m	High	Fixed
	Casing diameter at depth	4 1/2 - 9 5/8 in	>7 in	High	Fixed
	Distance to heat consumer	0-5 km	<0,5 km	Critical	Fixed
	Distance to heat source	0-5 km	<0,5 km	Critical	Fixed
	Well status	Active to abandoned	Temporarily abandoned	High	Fixed
Geological conditions	Geothermal gradient	20-80 °C/km	>40 °C/km	High	Fixed
	Rock thermal conductivity	1-4 W/m·K	2-3 W/m·K	Medium	Fixed

	Rock heat capacity	1,5-3,0 $MJ/m^3·K$	>2,5 $MJ/m^3·K$	Medium	Fixed
	Hydraulic conductivity	10^{-12}-10^{-5} m/s	<10^{-9} m/s	High	Fixed
	Groundwater flow velocity	0-100 m/year	<1 m/year	High	Fixed
Design parameters	BHE configuration	Various	Coaxial annular inflow	High	Optimizable
	Inner pipe conductivity	0,01-50 W/m·K	<0,1 W/m·K	Medium	Optimizable
	Grout conductivity	1,0-2,7 W/m·K	>2,0 W/m·K	Medium	Optimizable
	Working fluid	Various	Water	Low	Optimizable
Operational parameters	Flow rate	1-50 l/s	Site-optimized	High	Optimizable
	Charge inlet temperature	50-120 °C	As high as possible	High	Optimizable
	Discharge inlet temperature	30-70 °C	As low as possible	High	Optimizable
	Annual operating hours	0-8760 h	>4000 h	Medium	Optimizable

D. Workflow to reuse hydrocarbon wells as BTES with Deep Borehole Heat Exchangers

The conversion of an active or temporarily abandoned hydrocarbon well into a functional BTES system follows a structured workflow comprising seven major phases. This workflow is adapted from established oil and gas well workover practices but incorporates specialized steps for geothermal completion and surface integration.

D.1. Phase 1: Candidate Selection and Data Review

The initial phase involves systematic review of available well data to assess suitability for BTES repurposing. Key documents include final drilling reports, well logs, casing and cementing programs, wellhead diagrams, and any production history or workover records. The review should establish:

- Well construction details: casing sizes, setting depths, cement types and volumes, cement plugs

- Wellbore condition: casing integrity, cement bond quality, presence of scale or debris that blocks the well

- Geological data: lithological columns, formation temperatures, geothermal gradient, rock properties

- Completion details: perforated intervals, packer settings, tubing sizes and conditions

- Well status: current fluid levels, pressures, layer isolation status

- Assessment of surface logistics: site accessibility, proximity to heat sources and sinks, land ownership, existing surface infrastructure that might be repurposed.

D.2. Phase 2: Preliminary Feasibility Assessment

Based on the data review, a preliminary feasibility assessment evaluates the technical and economic viability of BTES repurposing. This assessment includes:

- Conceptual DBHE/BTES design: selection of inner pipe size and insulation type, estimation of achievable flow rates and pressure drops

- Thermal performance modelling: estimation of heat extraction and injection rates, storage capacity, and seasonal performance

- Integration concept: identification of heat source(s) and consumer(s), preliminary pipeline routing, surface equipment requirements

- Cost estimation: order-of-magnitude capital and operating costs

- Regulatory screening: identification of permitting requirements, land-use restrictions, and regulatory pathways

If the preliminary assessment indicates favorable feasibility, the project proceeds to engineering workover.

D.3. Phase 3: Well Workover and Preparation

The well workover phase mobilizes a workover rig to the site and prepares the well for BTES completion. Key activities include:

-Preparation or repair of the ~30 x 30 m work site and concrete re-works. Construction of an access road to the well if it is missing (abandoned well).

-Mobilization and Site Preparation: Transport workover rig and auxiliary equipment to location. Rig up over existing wellhead. Inspect cellar, conductor, and wellhead integrity. Install workover well control stack. Pressure test surface equipment.

-Well Kill and Securing: Confirmation that the well is static and fluid-filled. Verification of absence of sustained casing or tubing pressure. Pressure testing of existing tubing and annulus. Preparing a well for tubing recovery.

-Removal of Existing Completion: Removing of the eruption control equipment (*Christmas tree*) and production wellhead components. Installing workover BOP stack (series of blowout preventers installed at top of a wellhead to control well pressure and prevent blowouts during drilling operations) where needed. Releasing tubing hanger. Pulling existing production tubing in stands. Laying down tubing for inspection and disposal.

D.4. Phase 4: Formation Isolation and Wellbore Preparation

This phase isolates the original production zones to ensure a closed-loop system and prepares the wellbore for DBHE/BTES installation.

-Drifting of casing to full depth to ensure clearance for workover and placement of new tubing

-Formation Isolation: Running work string to depth of production intervals. Performing cement squeeze across perforated zones or open-hole sections to seal formation from wellbore. Displacing and cleaning up of excess cement. Waiting on cement and verification of isolation success by tagging cement top and pressure testing. Also, setting bridge plug on a wireline or slickline is also an option.

-Permanent Barrier Installation: Running permanent bridge plug on work string. Setting plug at depth above isolated intervals (typically just above the highest perforation). Applying setting procedure per manufacturer specification. Pressure testing from above to confirm isolation integrity.

-Wellbore Cleaning and Drifting: Cleaning out above bridge plug to remove any debris or cement residue. Confirming internal casing condition through caliper logging if warranted, or CBL-cement-bond log and acoustic log.

- Confirming wellbore remains fluid-filled.

D.5. Phase 5: Installation of the Deep Borehole Heat Exchanger for BTES

The core technical operation involves installing the coaxial DBHE completion.

-Tubing String Assembly: Making up the inner tubing string with centralizers spaced to maintain concentric position within the casing. For insulated completions, ensuring insulation integrity at connections. Recording accurate tally of installed lengths. Running tubing to planned depth, typically with the bottom of the string positioned just above the bridge plug.

-Tubing Hanger Landing: Landing tubing in tubing hanger at wellhead. Verifying correct depth and orientation. Pressure testing tubing to confirm integrity.

D.6. Phase 6: Wellhead Re-Commissioning and Surface Integration

-Wellhead Modification: Installing new or refurbished wellhead configured for coaxial operation. The equipment should provide separate access paths to the tubing (production leg) and casing annulus (injection leg). Installing pressure and temperature monitoring on both lines.

-Surface Equipment Installation: Installing surface equipment including plate or frame heat exchangers, control valves, circulation pumps, and if required, heat pumps system. Connecting to the district heating network and waste heat source via insulated buried or above-ground pipelines. Installing control system with capability for automated valve positioning and data logging.

D.7. Phase 7: Commissioning, Testing, and Monitoring

-System Filling and Venting: Filling the complete closed loop with working fluid (treated water, or alternatively some other fluids like ammonia or refrigerants depending on system design). Venting all high points to remove trapped air. Verifying fluid levels and pressures.

-Integrity Testing: Performing surface pressure testing of tubing and annulus wellhead components. Pressure testing the water-filled well as a closed-loop system to verify overall integrity and absence of formation communication. Circulating water down the annulus and up the tubing while monitoring pressures and flow stability.

-Thermal Response Testing: Conducting enhanced thermal response testing to validate formation thermal properties and DBHE thermal resistance. This involves circulating fluid at controlled temperatures while monitoring inlet and outlet temperatures and flow rates, enabling calculation of effective thermal conductivity and well resistance.

-Seasonal Commissioning: Operating the system through at least one partial charge-discharge cycle to verify performance under realistic conditions. Monitoring temperatures, pressures, flow rates, and energy flows. Comparing measured performance against model predictions and adjust control parameters as needed.

D.8. Timeline and Critical Path Considerations

The complete workflow from candidate selection to operational commissioning typically requires 12-24 months for a single well, depending on well condition, equipment availability, and regulatory timelines. The critical path typically includes:

- Regulatory permitting (variable, 3-12 months depending on jurisdiction)
- Workover rig availability and mobilization (1-4 months)
- Custom tubing manufacturing and delivery, particularly if VIT is specified (3-6 months)
- Surface equipment procurement and installation (2-4 months)

Project planning should incorporate contingency for unexpected well conditions, such as stuck tubing, casing damage, path blockage or cement integrity issues discovered during workover operations.

E. Feasibility analysis

The Savica-1 well in Zagreb, Croatia, serves as the primary pilot case for deep BTES repurposing within the TRANSGEO project (TRANSGEO Deliverable 2.3.5). This section presents a comprehensive feasibility analysis based on detailed site characterization, numerical modelling, and economic assessment.

E.1. Technical Feasibility Assessment

E.1.1. Description of the Savica-1 Well

Savica-1 was drilled in 1981 as an exploratory well to investigate geological conditions and assess the geothermal aquifer in the southeastern part of the Zagreb area. The well reached a total depth of 2,202 m.

Well construction features multiple casing strings:

- Surface casing: 13⅜" installed to 122,7 m, cemented to surface
- First intermediate casing: 9⅝" installed to 618,7 m, cemented to surface
- Second intermediate casing: 7" installed from 497,0 to 1744,0 m cemented section

-Open hole 1744,0 to 2202,2 m with diameter of 152 mm

This telescoping casing design provides progressively smaller diameters with depth, a common configuration in hydrocarbon exploration wells. For BTES repurposing, the 7" casing with length of 1247 m to total depth represents the majority of primary flow conduit and constrains the maximum size of inner tubing that can be installed.

Drill stem testing conducted in 1981 confirmed the presence of geothermal fluids with temperatures up to 94.4°C at depth. However, production tests revealed low brine production capacity, with flow rates of 0.63 L/s (DST 1), 2.38 L/s (DST 2), and 3.93 L/s (DST 3). These low flow rates, combined with the well's location in an industrial zone, led to its selection for BTES repurposing rather than conventional hydrothermal development.

E.1.2. Geological Setting and Thermal Properties

Savica-1 is located in the northwestern part of the Sava Depression, one of four major Neogene-Quaternary depressions in the Croatian portion of the Pannonian Basin System. The Sava Depression is characterized by thick Neogene sediments, locally exceeding 3,000 m, resulting from tectonic subsidence along marginal faults. The regional geothermal gradient at the Savica site is approximately 4°C/100 m, slightly above the global average of 3°C/100 m. This elevated gradient reflects the extensional tectonic setting of the Pannonian Basin and contributes to the favorable thermal regime for geothermal applications. Thermal rock properties were calculated using correlations developed by Jelić for the Sava Depression (Jelić, 1987). These correlations relate thermal conductivity to rock density. Combining these relationships yields depth profiles of thermal conductivity, volumetric heat capacity, and temperature that characterize the thermal regime at Savica-1.

E.1.3. Description of Heat Source and Customer

The Savica-1 well is situated in the Peščenica-Žitnjak industrial district of Zagreb, approximately 2 km north of the Sava River channel. This location offers exceptional advantages for BTES development due to its proximity to both heat source and potential heat consumers. The combined heat and power plant TE-TO Zagreb is located within the same industrial district, approximately 2 km from the well. This cogeneration plant produces electricity and district heating for the City of Zagreb, with substantial waste heat available during summer months when heating demand is minimal but electricity generation continues. This waste heat represents an ideal charging source for BTES, as it would otherwise be rejected to the environment. Potential heat consumers include the industrial facilities within the Žitnjak commercial zone, as well as residential and commercial buildings in the Peščenica district. The existing district heating network of Zagreb provides infrastructure for heat distribution, potentially enabling integration with a much larger customer base. The nearby old railway corridor, which served to deliver back-up fuel oil for the power plant, offers a potential route for district heating pipelines, minimizing land acquisition and construction challenges.

E.1.4. Numerical Modelling Framework

A comprehensive numerical modelling framework was developed to assess BTES feasibility at Savica-1. The framework couples transient simulation of three system components: surface equipment, borehole heat exchanger, and geothermal reservoir.

- Surface Equipment Model: The surface system comprises three heat exchangers: a main heat exchanger for direct geothermal heating, and two waste heat exchangers (WH-1 and WH-2) for utilizing industrial waste heat. WH-1 provides supplementary heating during the winter season when geothermal output is insufficient. WH-2 enables reservoir reheating during summer when excess industrial heat is available and heating demand is minimal. A high-temperature heat pump elevates the temperature of extracted geothermal heat when necessary, and electric heating provides final backup. Control valves at each heat exchanger regulate flow distribution, with valve openness ratios optimized to satisfy temperature constraints while maximizing system performance.

- Borehole Heat Exchanger Model: The BHE is modelled using a one-dimensional energy balance for coaxial annular inflow configuration. Two design variants were considered: a shallower completion to 1800 m utilizing wider casing sections, and a deeper completion to 2200 m utilizing the full well depth but with smaller diameter at depth.

- Reservoir Model: The geothermal reservoir is modelled using the finite element software FEFLOW. The model domain extends to 2,500 m depth with a radius of 500 m, discretized with refined mesh (0.5 m resolution) near the BHE. Boundary conditions are isothermal and no-flow, with a bottom temperature of 160°C, a top temperature of 12°C, and a linear lateral temperature distribution. This yields an effective geothermal gradient of approximately 40°C/km. The reservoir is modelled as dry rock with 5% porosity and zero hydraulic conductivity, reflecting the requirement for negligible groundwater flow to ensure effective thermal storage.

- Coupling Framework: Full coupling between surface equipment and reservoir models is achieved through a Python-FEFLOW interface. At each time step, a pre-time-step routine first computes the BHE mass flow rate and leaving source temperature from the surface-equipment energy balance; the FEM solver is then advanced; and a post-time-step routine reads the resulting entering source temperature from the reservoir model and stores all results before the next step begins. This coupled approach captures the dynamic interactions between surface operations and subsurface thermal response.

E.1.5. System Configuration and Performance Analysis

Four test cases were evaluated to assess the impacts of well depth and BTES reheating:

1. BHE1800-Ind-RehY: 1,800 m BHE with industrial waste heat and BTES reheating
2. BHE2200-Ind-RehY: 2,200 m BHE with industrial waste heat and BTES reheating
3. BHE1800-Ind-RehN: 1,800 m BHE with industrial waste heat, no reheating
4. BHE2200-Ind-RehN: 2,200 m BHE with industrial waste heat, no reheating

Annual energy results for the second year of simulation reveal substantial differences between configurations.

- Power Balance: The BHE2200 configuration exhibits significantly higher annual electricity consumption — approximately 0.41 GWh/yr with reheating and 0.45 GWh/yr without — versus 0.27 GWh/yr and 0.31 GWh/yr respectively for the BHE1800 cases, owing to higher hydraulic losses in the longer flow path and smaller tubing diameter. Within these totals, electric-heater consumption is larger for BHE1800 (0.060–0.065 GWh/yr) while heat-pump compressor consumption is larger for BHE2200 (0.242–0.275 GWh/yr). Reheating itself has only a small effect on total circulator electricity but redistributes consumption between heat-pump and electric-heater backup. Reheating shows minimal impact on total circulator electricity consumption but affects its distribution among components.

- District Heating Supply: Heat pump supply dominates district heating in all cases, contributing 50-76% of total heat depending on configuration. Direct geothermal supply is negligible for non-reheated cases but increases to approximately 15% with reheating. Waste heat (WH-1) provides the second-largest contribution, while electric heating remains a minor supplement.

- BHE Energy Balance: The reservoir supplies 60-80% of heat to the BHE out of the total system, with higher contribution from deeper wells. Reheating adds substantial heat input (250 MWh for BHE1800, 220 MWh for BHE2200) from waste heat via WH-2. Heat extraction from BHE is dominantly for heat pump supply, with smaller portions for direct heating when reheating is employed.

- Waste Heat Utilization: Reheating substantially increases total waste heat utilization, with WH-2 consumption similar for both BHE configurations. The lowest waste heat utilization occurs for BHE2200 without reheating. Across the four configurations, the BHE1800-Ind-RehY case offers the most balanced overall performance: it has the lowest annual electricity demand (~0.27 GWh), the highest total system COP among the cases tested, and makes effective use of summer industrial waste heat both for direct heating supply (WH-1) and for seasonal reservoir reheating (WH-2). The deeper BHE2200 cases recover more heat directly from the formation thanks to higher in-situ temperatures, but pay an electricity penalty through higher hydraulic losses; without reheating, neither depth captures the full economic value of available summer waste heat. The choice between configurations therefore depends primarily on the local cost of waste heat and electricity: BHE1800 with reheating is preferred when waste heat is cheap and electricity is expensive, while BHE2200 becomes more attractive when waste heat is constrained or costly.

E.1.6. BTES Storage Efficiency and Energy Balance

The BTES storage performance is evaluated by tracking energy accumulation within a 4 m radius around the BHE. Results demonstrate that:

- Without reheating, natural geothermal heat flux provides substantial thermal recovery: approximately 200 MWh for BHE1800 and 280 MWh for BHE2200 over an annual cycle.

- With reheating, an additional 250 MWh (BHE1800) or 220 MWh (BHE2200) can be stored, representing 625-550 additional hours of heating at 400 kW demand.

- System efficiency, measured by coefficient of performance (COP), shows total system COP slightly higher for BHE1800 than BHE2200. Heat pump COP remains approximately 7 for all cases, reflecting its dependence on temperature lift rather than absolute temperatures.

Detailed timeseries analysis for the BHE1800-Ind-RehY case reveals operational dynamics:

- Direct heating from BHE dominates during summer low-demand periods when entering source temperature exceeds leaving load temperature by at least 5°C.

- WH-2 reheating valve opens during summer, injecting waste heat into the reservoir.

- WH-1 covers heating demand above baseload BHE supply during winter.

- Electric heaters supply only peak thermal demands.

- Heat pump provides the majority of heating, requiring thermal output capacity of at least 180 kWth.

These results demonstrate that deep BTES at Savica-1 can effectively store and recover significant thermal energy, with reheating (subsurface heat storage by BTES) providing substantial performance benefits. The optimal configuration depends on site-specific priorities: longer tubing reduces waste heat requirements but increases pumping power; reheating improves direct geothermal contribution but requires additional waste heat availability.

E.2. Legal and Regulatory Feasibility

E.2.1. Spatial Planning Documentation Compliance

Analysis of applicable spatial planning documentation confirms that BTES development at Savica-1 is permitted under current regulations. The General Urban Plan of the City of Zagreb explicitly provides for:

- Use of geothermal energy within all land-use zones

- Construction of structures for thermal energy supply, including geothermal systems

- Laying of district heating pipelines within defined corridors (2-4 m width depending on pipeline diameter)

The well site is located within an industrial zone, where geothermal development is specifically contemplated. No conflicts with protected areas or significant landscapes are identified, as the site lies outside ecological network zones and Natura 2000 areas.

E.2.2. Concession and Permitting Requirements

A key legal advantage for closed-loop BTES systems is their favorable treatment under Croatian mining legislation. Because the system does not involve permanent production of geothermal water, it may not be subject to the same concession regime applicable to conventional hydrothermal production. The

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Hydrocarbons Exploration and Exploitation Act and associated fee regulations do not explicitly address closed-loop thermal storage, creating regulatory flexibility. However, this absence of explicit classification also introduces uncertainty. Project development would require engagement with relevant authorities (Ministry of Economy and Sustainable Development, Hydrocarbon Agency) to establish the applicable regulatory pathway. Potential approaches include:

- Classification as a geothermal energy utilization project with modified conditions due to closed-loop operation

- Classification as an energy storage facility under separate regulations

- Development of a bespoke permitting approach through administrative procedures

E.2.3. Environmental Regulatory Framework

Environmental impact assessment requirements depend on project scale and location. The relatively small footprint of a single-well BTES system—limited to the well pad (approximately 30×30 m), access roads, and pipeline corridors—suggests that a full environmental impact study may not be required. However, environmental screening would be necessary to confirm this determination. Key environmental considerations identified in the feasibility study include:

- Biodiversity: Minimal impact expected due to industrial location; temporary impacts during construction limited to vegetation removal and noise.

- Water Resources: Closed-loop design prevents contact between geothermal fluid and environment; fully cased and cemented well prevents aquifer contamination.

- Soil: Potential for localized, reversible contamination in event of fluid spill in case non-water fluid is used; remediation measures would address any incidents.

- Air Quality: No significant emissions during normal operation; dissolved gases (CO_2, trace methane) in geothermal fluid would be captured and reinjected if present.

- Waste Generation: Minimal waste during operation; construction wastes managed through authorized contractors.

E.3. Economic Feasibility Assessment

E.3.1. Capital Expenditure (CAPEX) Estimation

Based on a detailed engineering assessment, total capital investment for Savica-1 BTES repurposing is projected at approximately €3.1 million. Several observations regarding the cost structure merit attention. First, the well site preparation and well workover and tubing installation represents approximately 35% of total costs or even more, reflecting the specialized nature of deep BHE completion. These costs could especially be a problem for wells that are abandoned and need complete reconstruction of working perimeter, concrete slabs, infrastructure like roads or electricity supply. The current situation in most EU countries is not very good from the standpoint of revitalization workover rigs costs. Costs have been doubling since the pre-2020 era and do not show a tendency of plateau flattening. Secondly, pipeline infrastructure constitutes approximately 32% of total costs, underscoring the critical importance of proximity to both heat source and consumer. Third, documentation and permitting costs (7% of total) are substantial but necessary given regulatory requirements.

E.3.2. Operational Expenditure (OPEX) Estimation

Annual operating costs comprise several elements:

-Electricity Consumption: Power requirements include circulation pumps for the BHE loop and district heating loop, and the heat pump compressor. Total electricity consumption depends on operating strategy and system efficiency but is estimated to be around 40-80 kWe of installed power for a circulation pump, for a classic 3000-4000 m deep well with 9 5/8" casing, with consumption of around 50 MWhe/year based on modelling results. At Croatian industrial electricity prices (approximately €120/MWh), this represents €6,000 annually.

-Maintenance: Routine maintenance is estimated at 3% of annual revenue from thermal energy sales. This covers periodic inspections, equipment servicing, and minor repairs.

-Personnel: System operation requires part-time technician coverage, estimated at 0.5 full-time equivalent. Annual gross salary including overhead is estimated at €25,000.

-Insurance and Administrative Costs: Insurance premiums, property taxes, and administrative overhead are estimated at €5,000 annually.

-Contingency: An allowance of 5% of other operating costs is included for unforeseen expenses.

Total annual OPEX is estimated at €35.000 with the possible range reflecting uncertainty in electricity consumption and maintenance requirements.

E.3.3. Revenue Projections and Heat Pricing

Revenue derives from sale of thermal energy to district heating customers. The reference price for industrial heat consumers in Croatia is approximately €45.4/MWh based on HEP Toplinarstvo tariffs. For a BTES project, a discount from this reference price may be necessary to attract customers, but the actual achieved price depends on negotiation with specific consumers. Annual heat delivery is estimated at 2,000 MWh based on modelling results. At the reference price, this yields annual revenue of €90,800. Additional revenue may be available through renewable energy incentives or carbon credits, though these are not quantified in the base-case analysis. Combining the foregoing estimates, the base-case economics of the Savica-1 BTES are: total CAPEX ≈ €3.1 million; OPEX ≈ €35 000/yr; gross revenue ≈ €90 800/yr; net annual cash flow ≈ €55 800/yr. The corresponding simple payback period is approximately 55 years, which substantially exceeds typical investment horizons of 15–25 years. At current Croatian reference heat prices (€45.4/MWh), the project is therefore not commercially viable on energy-sales revenue alone. Three levers can bring payback into a viable range: (a) a higher achieved heat price — a sale price of approximately €70–80/MWh would reduce simple payback to below 20 years; (b) capital-grant support — typical EU schemes covering 40–60 % of CAPEX would shorten payback proportionally; and/or (c) monetisation of avoided CO_2 emissions through carbon-credit revenue or an industrial waste-heat fee paid by the heat producer. A combination of these instruments is likely needed for a commercially attractive case.

E.3.4. Risk Assessment and Mitigation Strategies

Qualitative risk analysis identifies key project risks and mitigation measures.

Technical risks are:

- Well integrity failure during workover: Mitigation through comprehensive pre-workover logging and contingency planning.

- Lower than expected thermal performance: Mitigation through conservative design assumptions and performance testing during commissioning.

- Equipment reliability issues: Mitigation through selection of proven components and maintenance planning.

Economic risks are:

- Heat price volatility: Mitigation through long-term heat purchase agreements with price adjustment mechanisms.

- CAPEX overrun: Mitigation through fixed-price contracting and contingency allowance.

- OPEX higher than projected: Mitigation through detailed operational planning and performance monitoring.

Regulatory risks are:

- Permitting delays: Mitigation through early engagement with authorities and comprehensive documentation.

- Regulatory changes: Mitigation through monitoring of policy developments and adaptive project planning.

Environmental risks are:

- Accidental fluid release: Mitigation through leak detection systems and spill response planning.

- Groundwater impact: Mitigation through well integrity assurance and monitoring.

E.4. Conclusions and recommendations related to BTES

E.4.1. Technical conclusions

1. Deep BTES is technically feasible: Numerical modelling and emerging demonstration projects confirm that repurposed hydrocarbon wells can effectively store and recover thermal energy on a seasonal basis. The Savica-1 analysis demonstrates achievable storage of 200-500 MWh per well annually, with reheating providing substantial performance benefits.

2. Coaxial BHE design is mature: Coaxial borehole heat exchangers with annular inflow represent a mature, reliable technology for deep BTES applications. Design parameters including inner pipe insulation, flow rate optimization, and control strategies can be specified with confidence based on existing experience.

3. Operational parameters are key: Sensitivity analyses consistently identify operational parameters like flow rate and inlet temperatures during charge and discharge as most influential on system performance. This finding implies that careful engineering and adaptive control can optimize performance even in suboptimal geological settings.

4. Storage efficiency is moderate: The proportion of injected heat recoverable in subsequent extraction cycles is modest (typically 30-50%), meaning BTES is most economic when charging heat is low-cost or otherwise wasted. This characteristic aligns well with industrial waste heat applications. Storage efficiency can be increased by deploying multiple wells in close clusters (typically a few meters to a few tens of meters apart). A cluster reduces the surface-to-volume ratio of the heated rock body and therefore limits conductive losses to the surroundings.

5. Well selection criteria are clear: Suitable wells must have adequate casing diameter (>7 inches at depth), sufficient depth (>1,000 m), favorable location relative to heat source and sink, and acceptable mechanical integrity.

E.4.2. Economic Conclusions

1. BTES repurposing is cost-effective: Capital costs for repurposing (€3.1 million for Savica-1) are substantially lower than greenfield deep drilling, which would cost €8-10 million for comparable depth when considering turn-key contracts without risk for investors. This cost advantage is the primary economic driver for well reuse.

2. Economic viability depends on heat price: Financial returns are sensitive to achieved heat prices, with viability requiring higher prices than current ones in Croatia. Long-term heat purchase agreements are essential for investment certainty, and they also provide tangible value to the heat customer, securing a predictable, locally-sourced and decarbonized heat supply at a stable price, insulated from fossil-fuel price volatility.

3. Proximity drives economics: Pipeline costs constitute approximately one-third of total capital expenditure in the case of repurposing Savica-1, confirming that short distances to heat source and sink are critical for economic viability.

4. Closed-Loop advantage: The absence of fluid production fees for closed-loop systems in some jurisdictions provides a significant economic advantage over hydrothermal alternatives.

E.4.3. Policy Recommendations

1. Clarify regulatory status: Policymakers should explicitly address closed-loop BTES systems in energy and mining legislation, providing clear permitting pathways and eliminating uncertainty regarding resource classification and concession requirements.

2. Develop well inventories: Public authorities should compile and maintain inventories of abandoned wells, including relevant technical data, to facilitate identification of repurposing candidates.

3. Support demonstration projects: Continued public support for demonstration projects is essential to build operational experience and validate performance predictions.

4. Address liability transfer: Clear frameworks for transferring long-term liability for repurposed wells from original operators to new geothermal operators would remove a significant barrier to project development.

5. Integrate with district heating planning: Regional and municipal energy plans should identify opportunities for BTES integration with existing and planned district heating networks.

E.4.4 Future Research Directions

1. Long-term operational data: As demonstration projects enter operational phases, collection and dissemination of long-term performance data will be essential for validating models and optimizing designs.

2. Multi-well arrays: Research should extend from single-well studies to multi-well arrays, investigating thermal interference, optimal spacing, and array configurations for larger-scale storage in case of entire hydrocarbon field revitalization after production ceases.

3. Advanced control systems: Development and testing of model predictive control systems that optimize BTES operation in real time could substantially improve performance.

4. Material improvements: Continued development of low-cost, high-performance insulation materials for inner tubing could improve thermal efficiency while reducing costs.

5. Integration with renewable electricity: Research into power-to-heat configurations that use surplus renewable electricity for BTES charging could enable deeper decarbonization.

6. Environmental monitoring: Long-term environmental monitoring at demonstration sites should track subsurface temperature evolution, groundwater conditions, and ecosystem responses to validate environmental performance.

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