Integrated decision-support system for reliable geothermal project assessment

Terence Coudert[1], Hieu-Nguyen Hoang[1], Steinar Haugland[1], Torgeir Ustad[1], Alexandre Morin[1], M.A.H. Chowdhury[2], Ebrahim Mohammad Saleh[2], Lilja Tryggvadóttir[3], Gunnar Kaldal[4], Steinthór Níelsson[4]

[1] SINTEF Industry, P.O. Box 4760 Torgarden, NO-7465 Trondheim, Norway.

[2] Technovative Solutions Ltd., Unit 1 and 4, Rutherford House, Manchester Science Park, M15 6JJ, UK.

[3] Reykjavik Energy, Bæjarháls 1, 110 Reykjavík, Iceland.

[4] Iceland GeoSurvey ÍSOR, Urdarhvarfi 8, 203 Kópavogur, Iceland.

terence.coudert@sintef.no

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ABSTRACT

Deep geothermal energy projects, especially those tapping into superhot reservoirs (>450°C), have great potential for large-scale power generation, with individual wells producing 40-50 MW. However, the extreme conditions (high temperatures, pressures, and corrosive fluids) challenge well integrity and durability. Current technologies, adapted from the oil and gas industry, are inadequate, as shown by failures in projects like the Iceland Deep Drilling Project (IDDP). The COMPASS project aims to address these issues by developing a digital, cloud-based platform for integrated well design and decision support. This platform will enhance well concept design, material selection, and investment decisions, using advanced models for well cement behavior, wellbore thermodynamics, structural integrity, and cost and life cycle assessment (LCA). The decision-support system (DSS) will integrate these models to provide comprehensive data, risk assessments, and acceptance criteria. Applications of the DSS in the geothermal industry include well concept design, material selection, investment decision support, risk assessment, optimization of geothermal exploitation. These applications aim to improve the efficiency, safety, and sustainability of geothermal energy projects.

1. INTRODUCTION

Deep geothermal energy, particularly from depths greater than 3 km, offers significant potential for high energy output by extracting high enthalpy geofluid. When drilling into superhot rocks near magma resources, where temperatures range from 450°C to 600°C, each well can produce up to 40-50 MWe. However, the main obstacles to exploiting geothermal energy from these near-magma resources are the lack of reliable drilling and completion technologies and the absence of standards regulating geothermal well construction, especially under superhot conditions. The harsh operational conditions in superhot geothermal reservoirs, characterized by high temperatures, high pressures, and corrosive geofluids, pose significant challenges to well integrity. Improper material selection and design principles can lead to serious failures and the loss of production wells, as seen in many geothermal projects (Kruszewski and Wittig 2018; Ford et al 2019). For example, the Iceland Deep Drilling Project (IDDP) faced severe well integrity problems in its initial wells, preventing their use for power production. Additionally, numerous casing failures in conventional geothermal wells highlight the need for improved well construction technologies, which are currently adapted from the oil and gas industry. To address these challenges and bridge the knowledge gap in geothermal well design, the COMPASS project (https://compass-geothermal.eu/) aims to develop an efficient, flexible, and accurate design tool integrated with a digital decision-support system (DSS). This tool will enhance the understanding of the interplaying physics in geothermal wells, both conventional and superhot/supercritical, and propose optimal strategies for sustainable and robust well design and exploitation. The COMPASS project will develop integrated design software with several modelling modules and computational steps addressing different well life events, including drilling, completion, operation, and maintenance. Key components of this software include:

1. Advanced well cement models: These models will predict the behaviour of foam cement in geothermal field conditions, including hydration and set-cement behaviour under confining pressure and superhot temperatures. Experimental data will be used to calibrate these models.

2. Wellbore thermic module: This module will model multiphase flow and thermodynamic behaviour of geofluids to predict temperature and pressure changes

in the wellbore during different well life events. The models' prediction capabilities will be verified using data from geothermal wells and field tests.

3. Well structural integrity modelling tool: This tool will assess the integrity of critical well components, such as cement, casing, and couplings, in superhot geothermal wells. It will integrate information from various mechanisms in the wells into structural analyses, using inputs from material tests and validated by specific tests.

4. Parametric cost and LCA models: The parametric cost models for well completion and surface plants have been developed based on the Geothermal Electricity Technology Evaluation Model (GETEM) framework (Mines G.L., 2016). The cradle-to-gate life cycle assessment (LCA) model for well completion and the cradle-to-grave LCA model for surface plants have been developed based on ISO LCA standards (ISO 14040, 2006a and ISO 14044, 2006b). The functional unit of cost and LCA studies for well completion is 1 meter of drilling activities. The functional unit of cost and LCA studies for surface plants is 1 MWh of electrical energy production.

The result of this research will be a digital, web-based DSS that supports the evaluation and selection of optimal strategies for geothermal well design and exploitation. The DSS will integrate results from various models, providing a comprehensive overview of analysed data, risks, and acceptance criteria for different scenarios. An API integration process will enable efficient data exchange and collaboration, enhancing the development of new software solutions for the geothermal industry. The DSS, as illustrated in Figure 1, will utilize at least three APIs to group specific simulation tools and databases, ensuring a robust and user-friendly platform for geothermal well design and exploitation.

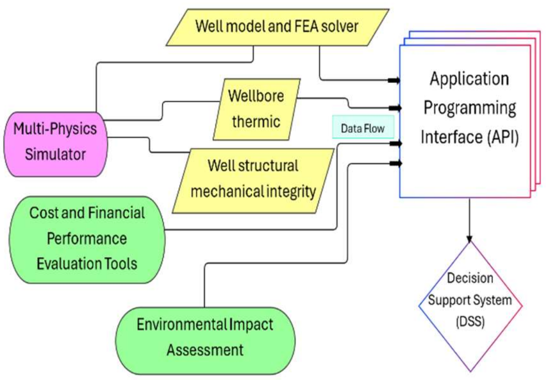

Figure 1. Integration of various tools within the Decision Support System using an Application Programming Interface (API).

2. MULTI-PHYSICS SIMULATOR

The developed simulator consists of two main components: (i) a well integrity structural solver, *casinteg,* a finite element-based analysis solver to compute the stress state of the well components; (ii) a multiphase flow solver to predict the temperature and pressure inside the well bore during energy production.

Casinteg is a finite element-based software adapted for structural analyses of the global behaviour of wells, with an emphasis on high-temperature wells. The software solves for mechanical equilibrium, and for heat diffusion (including transients in the heat diffusion). Casinteg is intended for the study of thermal expansion and possible slip at contact interface between layers in the well. To this effect, it must resolve the contact pressures between the layers but also be able to consider nonlinear properties of casing and cement materials.

2.1 Well model and FEA solver

Hoang et al. (2021) describes theory of the FEA solver casinteg and demonstrates the benefit of casinteg for efficient structural analyses of full geothermal wells. The casinteg simulator assumes geometrically axisymmetric structures and uses a cylindrical coordinate system. Heat transfer is considered only in the radial direction, and the problem is assumed to be static. The numerical solving scheme involves implicit methods and Newton-Raphson iterations. The FEA solver uses simplified 2D axisymmetric elements to represent continuum materials. The heat transfer model is based on thermal conduction using the second Fick's law. Special gap elements are used to model contact between continuum bodies. The casing material models includes thermo-elastic, thermo-plastic, and thermo-plastic-creep models. The cement material models describe cement behaviour at different phases, including hydration and set cement behaviour. The poromechanical concept for set-cement models is implemented, so that the behaviour of set cement in undrained conditions can be modelled. The annular fluid model assumes the annular fluid as liquid, and accounts for pressure changes due to thermal expansion. The stress states of the well components (casing and cement) are predicted by casinteg and these stress states are post-processed to assess the well integrity of the well (see section 2.3).

2.2. Wellbore thermic

Casinteg can use pre-specified wellbore boundary conditions, but using a flow solver to calculate the boundary conditions is more realistic. Casinteg has therefore been adapted to using a flow solver to solve the flow field and energy in the wellbore fluid. The flow solver is an extension of a point model described in Smith et al. (2015). The point model is based on the Unit Cell Model (UCM) concept and was implemented by Ivar Eskerud Smith. The point model was originally developed for simulations of oil & gas pipes but was adapted to geothermal wells in COMPASS.

The main features of the original point model are:

- One-dimensional steady-state flow.
- Support for three fluid phases (gas, liquid oil and liquid water). The two liquid phases have their own fluid properties, but are combined

into a liquid mixture, so the flow is single-phase or two-phase (gas and/or liquid).

- The UCM concept is used for determining the local flow regime.
- The mass equations for the phases are solved, yielding the phase mass flow rates. Mass sources and sinks can be specified, but phase changes are not included.
- Simplified momentum equations for gas and liquid are used to construct an implicit equation for the liquid holdup. The calculated phase volume fractions are then used together with regime-specific relations to determine the pressure loss inside each cell along the wellbore, and the pressure is then solved for by marching backward from the outlet, where the pressure must be given.
- The fluid energy is not solved for. The energy is represented by a temperature profile boundary condition.
- The fluid properties of each phase are determined from either a PVT table or an equation-of-state (EOS), using the calculated pressure and given temperature as input.

The adaption of the original flow solver to COMPASS consisted of the following tasks: (1) adding an energy equation; (2) adding an EOS solver for pure water; (3) adapting the point model; (4) creating an interface to communicate between casinteg and the flow solver.

The energy equation is based on the specific enthalpy of the fluid mixture, since pressure and temperature can't alone resolve the two-phase region for pure water. It calculates the fluid temperature profile and uses it with the wellbore wall temperature profile and flow regime-specific relations to calculate the local fluid-wall heat fluxes.

The EOS is a C++ conversion of the MATLAB implementation of the IAPWS IF97 EOS for pure water by Mikofski (2013). It uses pressure and either fluid temperature or fluid specific enthalpy as input.

The point model was rewritten to use the new EOS. The first time it is run it calls the EOS solver with pressure and temperature, since an initial specific enthalpy field is unavailable. In all subsequent calls the latest calculated specific enthalpy values are used instead of temperature.

The communication interface consists of code that runs the extended flow solver and code that exchanges information between casinteg and the flow solver.

The wellbore flow is solved iteratively by alternately running the point model and solving the energy equation. These two steps are run until both the pressure profile, specific enthalpy profile and fluid-wall heat flux values have converged. In the point model step the flow field and fluid properties are iterated on by alternately calling the EOS (to update the fluid properties) and solving the flow field equations. The specific enthalpy is assumed constant during this step. In the subsequent energy equation step the current flow field and fluid properties are considered constant. When new specific enthalpy values have been calculated, the EOS determines the phase volume fractions and the corresponding phase changes are included in the next run of the point model as phase source/sink terms.

The communication between the flow solver and casinteg is done through a dynamic/shared library. Casinteg initially calls this library to define the wellbore geometry and initial fluid state. Since the flow solver is steady-state, casinteg is responsible for handling the transient information. This is done by casinteg calling the flow solver once per time step and assuming that the returned steady-state solution applies throughout the time step. Casinteg provides the flow solver with the wellbore inlet mass flow rate and temperature, the wellbore outlet pressure, and the temperature profile of the inner surface of the wellbore wall. The flow solver in return provides casinteg with the pressure profile and the fluid-wall heat fluxes.

Since the fluid-wall heat fluxes act toward equalizing the fluid and wall temperatures, they are self-reducing. That is, a given temperature difference causes a given heat flux, which causes a smaller temperature difference, which causes a smaller heat flux, and so on. This effect is neglected during a time step if constant heat fluxes are assumed throughout the time step. If the time step is small this is usually not an issue, but if the time step is long and the temperature differences are small, unphysical and destabilizing overshoots can occur, when smoothly stabilizing temperature profiles are expected. This is the well-known general issue of using explicit numerical schemes. To mitigate this issue, casinteg is allowed to adjust the given heat fluxes during its iterations on the structural temperature profile, making the coupling somewhat implicit instead. The adjustments in the heat fluxes correspond to changing wall temperatures, while assuming that the fluid temperatures and heat transfer coefficients remain unchanged.

Some verification tests have been conducted on the extended flow solver and the coupling to casinteg. The tests were conducted on a case where the fluid flowed upward through a 500 m deep vertical well, divided into 50 wellbore cells of 10 m length. The wellbore inner diameter was 55 cm and pure water flowed into the well at the bottom.

Figure 2 shows three tests with different heat transfer correlations. The mass flow rate in all three tests was 3 kg/s and the inlet water temperature was 200°C. In all three tests the fluid started out as liquid water and gradually evaporated into pure steam, cf. the curves from left to right. The cyan curve shows the fluid evolution for a constant heat flux from the wall to the fluid of 12 kW/m throughout the well and an outlet pressure of 4 bar. The magenta and black curves are for uniform wall temperature 350°C throughout the well and an outlet pressure of 20 bar. Without any dedicated

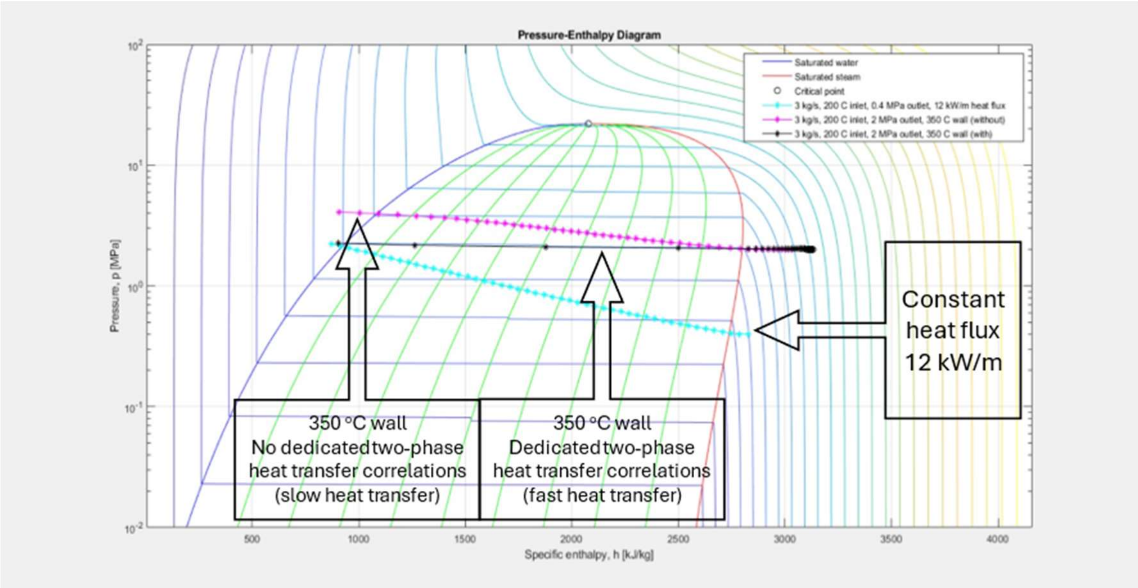

Figure 2. Pressure-enthalpy diagram showing three tests of the fluid-wall heat transfer in the flow solver when passing through the two-phase region.

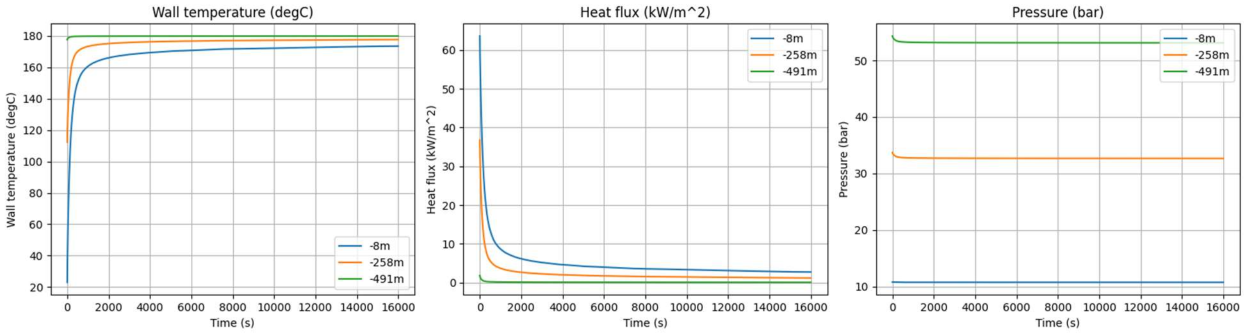

Figure 3. Wall temperature, heat flux and pressure in the coupled simulation test case.

two-phase heat transfer correlations (magenta curve), the transition from liquid to steam takes most of the well height to complete, while with dedicated correlations (black curve) the evaporation is much quicker and takes just a few cells to complete.

To verify the coupling between casinteg and the flow solver, a pure liquid case with a mass flow rate of 40 kg/s and an outlet pressure of 10 bar was run. Figure 2 illustrates the results of the simulation where the wall temperature is predicted by casinteg and the heat flux and pressure are predicted by the flow solver, and the system is converging to a steady state (see Figure 3).

2.3. Well structural mechanical integrity

For the casing integrity, different failure modes can occur: (a) burst occurs when internal pressure exceeds external pressure. This can happen during well control operations or cooling phases; (b) collapse happens when external pressure is higher than internal pressure, leading to compressive hoop stresses; different collapse modes are observed depending on the stiffness of surrounding materials; (c) axial buckling is driven by axial compressive stresses, especially in high-temperature wells, various buckling modes are identified based on unsupported casing length. (d) fatigue is mainly driven by thermal stress due to temperature cycling. High-cycle fatigue (HCF) and low-cycle fatigue (LCF) regimes are considered, with special attention to threaded connections. (e) low-cycle thermo-mechanical fatigue is evaluated on components subjected to large temperature cycles, incorporating creep and oxidation effects.

The upper part of the graph in Figure 4 represents the risk for casing burst, meaning the inner pressure P_i is greater than the outer one P_e, while the lower part represents the risk for casing collapse with $P_i<P_e$. The readers are referred to API TR 5C3 (2018) and Goodman et al. (2018) for more details. As for casing burst, collapse is also the failure mode mainly driven by the differential pressure in the radial direction. However, in contrary to casing burst, this failure mode occurs when the pressure on the external casing surface is higher than the pressure applied on the inner side, resulting in compressive hoop stresses in the casing, i.e.

the lower part in Figure 4. This casing collapse resistance is also dependent of the axial stress in the casing. This is accounted for in the API TR 5C3, as illustrated by the yellow curve in Figure 4. Casing axial buckling is a failure mode caused by axial compressive stresses, often due to increased temperature, such as during well heat recovery. When casing is not cemented at certain depths, it is at risk of buckling. Longer unsupported casing lengths require lower temperature loads to induce instability. High temperature wells with long unsupported lengths are more prone to elastic buckling, which has lower resistance to temperature changes compared to plastic buckling. The corresponding acceptance limit is illustrated by the green vertical line in Figure 4. The stress states of the well are illustrated in the Figure 4 by the green, red, and blue dots. Each color corresponds to a stress state at a given time of the life of the well. One dot corresponds to one element in the casing part of the FEA simulation. The user can then assess the risk of failure using the Figure 4, the risk is higher is the dots are close to acceptance limit curves.

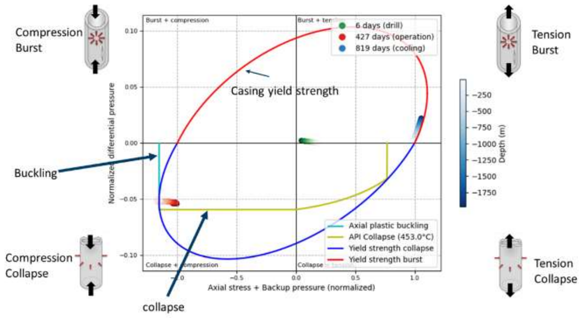

Figure 4. Casinteg post-processing tool that follows the API TR 5C3 (2018) acceptance criteria for casing.

A fatigue analysis post-processor for lifetime estimation for critical components is under development. In geothermal wells the main driver of fatigue is the thermal stress induced by the temperature-cycling, and the critical components are generally not the casings themselves, but the threaded connections of the casing couplings. The threads have very fine geometry and several designs are available, hence they are not modelled explicitly in Casinteg, and a notch correction approach is used instead. The necessary stresses, strains and temperatures are extracted from Casinteg and used to conduct fatigue analysis during post-processing.

For the High-Cycle Fatigue (HCF) regime (more than 10e4 cycles), a fatigue analysis procedure based on DNV-RP-C203 has already been implemented in Casinteg. Axial stresses are extracted from FE results and are notch corrected using stress concentration factors for a given type of coupling, and the stress amplitudes are calculated. Corrections for mean stress and temperature effects (using the cycle-averaged temperature) are applied, before calculation of component lifetime using one of the several available SN-curves from DNV-RP-C203.

For fatigue analysis in the Low-Cycle Fatigue (LCF) regime (less than 10e4 cycles) there is ongoing work on implementing a notch plasticity correction in the Casinteg post-processor. The plasticity correction will describe the notch plastic behavior for a given connector geometry at high thermal loads and allow for calculation of relevant variables for LCF analysis. Thermal LCF methods found in the literature can be grouped into damage-based, strain-based and energy-based, all of which can be computed using the information obtained from the plasticity correction, along with the relevant material fatigue data. Other high-temperature phenomena, such as creep or oxidation may be addressed in the future.

For the cement integrity, the tool estimates the permanent (a) deformation and damage, the cement can deform plastically beyond its yield limit, leading to shear and compaction damage; (b) pressure and temperature cyclic loading can create microannuli at material interfaces, potentially leading to leakage pathways.

3. COST PERFORMANCE

Cost performance tools have been developed for well completion and surface plants in geothermal energy systems using COMPASS technology components, such as casing with the application of laser cladding, cementing materials, and surface pipes, with ongoing work on flexible coupling.

1. For well completion, a parametric cost model is used to estimate the costs of laser cladding, casing and cementing materials across different intervals of drilled depth. The calculation considers the length and diameter of the casing, bit clearance, material grade, and density. Additionally, the model incorporates the costs of cementing materials, freight, and related services, resulting in a functional cost per meter of drilling activities for well completion. The user can assess the parametric cost model in COMPASS DSS, as shown in Figure 4.

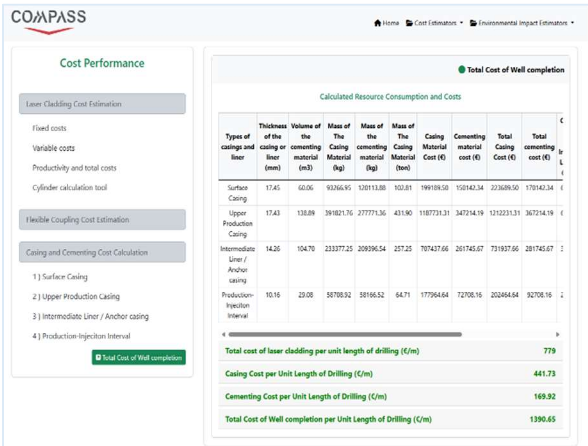

Figure 5. Cost Estimation of Laser Cladding, Cementing, and Well Completion by COMPASS DSS.

2. For evaluating the financial assessment as shown in Figure 5 of existing or future geothermal systems, a cost

performance tool for surface plants is developed based on parametric cost model within the GETEM framework (Mines 2016). This tool can estimate the capital cost of a geothermal system that comprises various cost components such as surface equipment, field gathering system, power plant, transmission, exploration, and drilling costs. It also calculates the levelised cost of electricity (LCOE) and other financial metrics such as Net Present Value (NPV), Payback Period, Internal Rate of Return (IRR), and Return on Investment (ROI) for a chosen geothermal system extracting hot or superhot geofluid. In addition, it can compute sensitivity analysis of NPV, PBP, IRR and ROI against discount rate, revenue factor and annual cash flow increase/decrease for the chosen geothermal system. The assessment of these metrics enables investors to evaluate profitability, risk, and potential returns, ensuring data-driven decision-making for strategic investments in existing or future geothermal systems.

Figure 6. Financial assessment of a geothermal plant using COMPASS DSS

4. ENVIRONMENT IMPACT ASSESSMENT

The environmental impact estimators for well completion and surface plants are developed based on ISO LCA standards (ISO 14040, 2006a and ISO 14044, 2006b). These estimators use the SimaPro LCA tool (SimaPro 2024) and the life cycle impact assessment (LCIA) methodology IMPACT 2002+ v2.15 (Jolliet et al. 2003) to evaluate environmental performances of existing or future geothermal system.

1. For the well completion, the resource consumption is estimated with the users' inputted or default data for casing and cementing materials, including types, lengths, masses, diameters, and densities. This environmental impact estimator for well completion evaluates environmental impacts for 1 meter of drilling activities. It provides quantification of environmental footprint, characterisation, damage assessment, and single score results in terms of 1 meter of drilling activities, as shown in Figure 6.

2. For evaluating the environmental impacts of existing or future geothermal systems extracting hot or superhot geofluid, an environmental impact estimator for surface plants is developed following a cradle-to-grave life cycle approach. This estimator can calculate the resource consumption data in construction, operation & maintenance and end of life phases of a chosen geothermal system using reference flow data of materials and processes from a representative geothermal system and user-inputted data for the chosen geothermal system. The functional unit of the cradle-to-grave LCA studies is 1 MWh of electrical energy production from the chosen geothermal system utilising hot or superhot geofluid. After analysing the resource consumption data for the chosen plant, this estimator employs background processes for various materials and processes from databases, such as ecoinvent and other databases. The LCIA methodology IMPACT 2002+ v2.15 translates these resource consumption data in three phases of a chosen plant into several environmental performance indicators such as climate change, human health, ecosystem quality and resources in terms of 1 MWh of electrical energy production using SimaPro LCA tool.

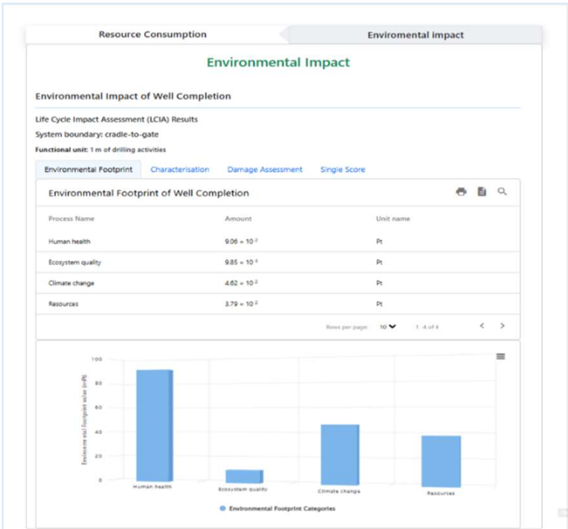

Figure 7. Visualisation of Life Cycle Impact Assessment (LCIA) Results, Including Environmental Footprint Characterisation, Damage Assessment, and Single Score.

5. DECISION SUPPORT SYSTEM

For an efficient workflow integrating the model set-up, flow-structure analyses, post-processing and well integrity assessment, a user-friendly graphical user interface is under development. This section provides a brief overview of the possible functionalities in the DSS web application. The web app in structured in modules. A module allows the user to prepare inputs or visualize outputs of an analysis. Each module is accessible in the top menu of the web app page. To prepare an analysis and run a simulation study, the following steps needs to be completed: (1) define the well geometry and the material properties of the well in "Wellbore" module (see Figure 8); (2) define the temperature and the pressure profiles in the wellbore (applied on to the inner surface of the innermost casing/tubing) during the different phases of the well lifetime ("Loading" module); (3) submit the finite element analysis in the "FEA" module (see Figure 9); (4) analyse the well mechanical integrity in the "Well integrity" module (like in Figure 4); (5) view the economics and life cycle assessment in the "Economics models" module (like in Figure 5, 6, and 7).

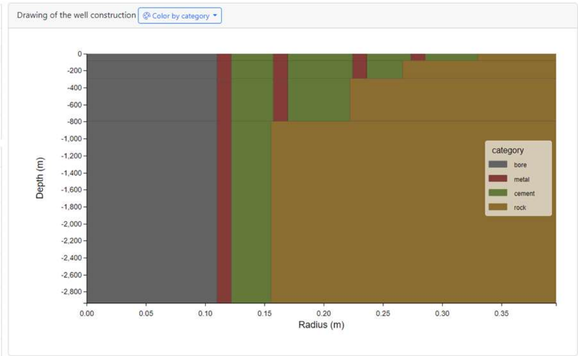

Figure 8. Drawing of each block of the well construction model.

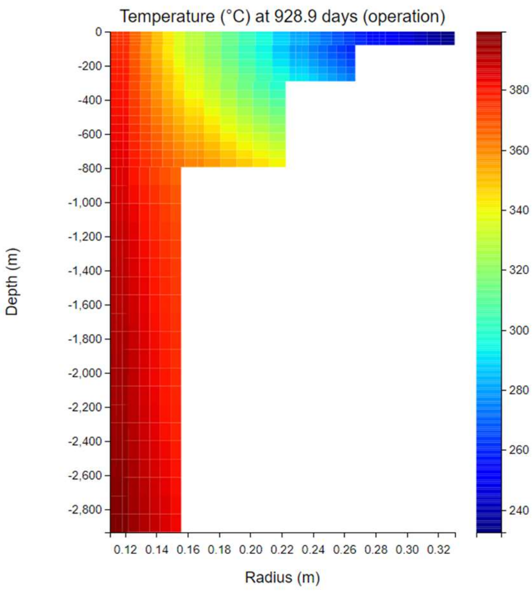

Figure 9. Example of FEA results, temperature field at the end of the "operation" phase.

6. CONCLUSIONS

This research work aims to develop a digital, web-based decision-support system (DSS), which will help in evaluating and selecting optimal strategies for sustainable and robust geothermal well design and exploitation. The DSS will integrate results from various models, providing a comprehensive overview of analysed data, risks, and acceptance criteria for different scenarios. A multi-physics well simulator *casinteg* which is integrated in the DSS and under development, will enable efficient data exchange and synchronization, enhancing collaboration and creating new software solutions for the geothermal industry. The first tool of the DSS includes two main components: (i) a well integrity structural solver (casinteg), which is a finite element-based solver for computing the stress state of well components; (ii) a flow solver which is a multiphase flow solver for predicting temperature and pressure inside the well bore during energy production. The software casinteg is, then, a specialised finite element software designed for comprehensive structural analysis of high-temperature wells. It addresses mechanical equilibrium and heat diffusion, including transient states, and focuses on thermal expansion and inter-layer slip. The software effectively resolves contact pressures and accommodates nonlinear material properties of casing and cement.

The second tool of the DSS implements a cost and Lifecycle Assessment (LCA) models for well completion and surface plants. It employs parametric cost models to identify key cost drivers for well completion and surface plant development. The LCA modelling for well completion follows a cradle-to-gate approach, focusing on the masses of casing, cementing materials, metalworking, and transportation, with 1 meter of drilling activities as the functional unit. For surface plant development, a cradle-to-grave LCA study evaluates environmental impacts throughout the entire lifecycle. The combined environmental analysis for well completion and surface plants provides insights into material use and emissions at different stages of geothermal energy development. The cost estimator highlights the cost complexity associated with exploration, drilling, and surface plant development, as well as the influence of site-specific factors on leasing and drilling success rates. Integrating these cost and environmental impact estimators for well completion and surface plants offer stakeholders a comprehensive framework to optimise financial and sustainability decisions, enhancing the economic viability and environmental performance of geothermal projects utilizing superhot geofluid from deep geothermal wells.

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