

# GEMINI model, module, and application implementation report

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**Disclaimer:** deliverables D2.1, D2.2, and D2.3 of the Nieuwe Warmte Nu! GEMINI project contain or discuss developed models that have been delivered to the consortium members as a formal project deliverable via a shared access link to the project Github: <https://github.com/GEMINI-Digital-Twin>. All partners currently have access to the repository. At the publication date of this deliverable, the models remain restricted to consortium partners; however, they are planned to be released as open-source in a subsequent phase, after which the public open-source version will become the primary reference for all further development beyond the current closed repository.

# Executive summary

This report presents the development, implementation, and integration of a geothermal plant digital twin. The development was based on TNO in-house developed digital twin framework, called GEMINI geothermal digital twin, which is a modular, real-time framework designed to enhance operational monitoring, engineering analysis, and asset management in geothermal systems. The GEMINI geothermal digital twin has been further expanded and developed as a comprehensive and modular framework designed to integrate both existing and newly created physics-based and data-driven models. This report outlines the full modelling architecture, detailing the governing equations, required inputs, produced outputs, and the assumptions and limitations associated with each component. Where validation data were available, benchmarking procedures were included to establish model performance boundaries and clarify appropriate usage conditions.

The implemented model suite covers the essential subsystems of geothermal operations, including reservoir inflow modelling, wellbore hydraulics, production performance calculations, well integrity management system, corrosion-risk estimation, and distributed temperature sensing (DTS) data ingestion and processing. These models have been embedded into a real-time computational environment that continuously processes live operational data. In addition, interactive offline applications and visualization dashboards allow engineers to perform scenario analysis, sensitivity assessments, and system diagnostics outside of real-time operations.

The digital twin can deliver operational and strategic value across production management, well-integrity assurance, and subsurface monitoring. Its production-monitoring capabilities improve insight into well and plant behavior, enable early detection of anomalies, and support production optimization and maintenance planning. Through the Well Integrity Monitoring System (WIMS) developed by Well Engineering Partners (WEP), the framework integrates multiple data sources to evaluate barrier envelopes, calibrate corrosion models against historical logs, and provide predictive insights into well integrity risks. DTS data handling is standardized to support consistent visualization and interpretation of temperature profiles, which is particularly valuable for subsurface performance monitoring and thermal energy storage applications.

The GEMINI platform is released as an open-source deliverable, ensuring transparency, extensibility, and community involvement. While the current models provide a robust foundation, several limitations define the present maturity of the system, such as simplified brine PVT behavior, linear IPR assumptions, steady-state formulations, and the need for further corrosion-model validation. These constraints serve as clear guidance for future development rather than diminishing the capability of the current framework.

Looking ahead, the digital twin will continue evolving through expanded monitoring coverage for surface-plant components, improved forecasting models for equipment degradation, refinement of corrosion and erosion modelling within WIMS, and broader field validation. Continuous updates to the open-source codebase, informed by field feedback and community contributions, ensure that GEMINI remains aligned with operational needs and technological advancements across the geothermal sector.

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# 1. Introduction

A digital twin is a virtual copy of a physical system or asset that allows an operator to monitor and model said physical system in a continuous (real-time) setting while simultaneously providing feedback back to the physical system in the form of (suggested) control actions and/or advice to the operator. A digital twin connects directly to data coming from sensors in the physical system, and uses internal (physical or data-driven) process and unit models to perform calculations using this data. These calculations can be used in a variety of ways, including the determination of up-to-date key performance indicators, monitoring of critical processes, anomaly detection, forecasting and optimization, and running scenario analyses. Ultimately, the goal of the digital twin is to use the data and calculated values to provide actionable insights or recommendations to the system's operator that can help them improve the efficiency and effectiveness of their system. This can be in the form of optimizing operational conditions or parameters, detecting off-normal events, and anticipating possible future events to help plan interventions and improve plant management.

While digital technologies have seen widespread use in a diverse array of applications, they have as of yet seen limited use in the geothermal sector. The focus of the Nieuwe Warmte Nu! (NWN) project is to develop and implement a digital twin architecture, based on TNO in-house framework called GEMINI, for deep geothermal plants. Primarily focusing on doublets (configuration with a pair of production and injection wells) in low-enthalpy environments that are suitable for direct use heating applications. The scope of the GEMINI digital twin is to support operation and maintenance (O&M) of geothermal plants. This will enable monitoring and simulation of plant operations, allowing for performance optimization, optimized maintenance planning, and risk mitigation in plants where operation can be complex, operational experiences are fairly limited considering the number of running geothermal doublets, and economic margins are tight. With the development of the digital twin as an open-source solution, the project aims to boost the uptake of digital technologies within the geothermal sector, and help its growth in the future.

An essential part to such a digital twin is a collection of models that can simulate the processes underlying the operation of geothermal systems. In addition, these models should be operationalized through modules and applications that allow the operators and engineers to get insights from the plant in real-time and interact with them in an offline manner for scenario analysis.

Work Package 2 of the GEMINI Digital Twin project focused on the development of new models and functionalities and adoption of existing models to be integrated into the digital twin framework of GEMINI. Together, the existing and new models covered three key capabilities of the digital twin:

- **Production monitoring**, which serves as an input to the predictive maintenance, including functionalities for productivity monitoring and modelling, as well as ESP (Electrical Submersible Pump) models.
- **Well integrity management system (WIMS)**, containing functionalities for log-based corrosion rate calculation and extrapolation, and tracking of the well's history and monitoring well integrity limits.
- **Subsurface monitoring**, focused on monitoring of high-volume subsurface DTS (Distributed Temperature Sensing) data.

In addition, unstructured text data processing functionalities for analysis and querying of reports have been developed within the Nieuwe Warmte Nu! project. However, as these are further detailed in a separate deliverable report (Deliverable 2.3), these are not further covered in this report.

Each of the above-mentioned topics will be covered in more details in separate sections of this report. This document is structured as follows: Section 2 gives an explanation of the differences between the terms "model", "module", and "application", and provides an overview of key functionalities of the general digital twin framework. Section 3 details a number of fundamental models that are used by other models in the digital twin (e.g. fluid property calculations, pressure drop relations, etc.). Sections 4 through 7 cover each of the separate functionalities previously discussed, including productivity

monitoring, , ESP monitoring, the WIMS, and the subsurface monitoring applications. Each of these sections will discuss the models used by the applications, and how the application was implemented in GEMINI. The document ends with a section on the main conclusions from the work and a look ahead at potential future developments that could be made.

Finally, it should be noted that this document focusses on describing the models that were developed (which equations/relations were used, how they are used, their limitations, etc.), and how they were implemented in modules, and various applications within the GEMINI digital twin. This document does not aim to serve as a technical guide on installing and/or contributing to the open-source version of GEMINI, nor does it cover the source code documentation. It is also not intended to be a comprehensive user manual of the digital twin. This can all be found, when finalized, in the technical user manual published at the following address: <https://gemini-digital-twin.github.io/gemini-geothermal-suite-open/main/>. In addition, the final open-source release of the GEMINI codebase can, once published, be found here: <https://github.com/GEMINI-Digital-Twin>.

## 2. General framework

Before going into the model and application details, it is good to have a basic understanding of how they relate to the GEMINI digital twin in its entirety. Therefore, this section provides an overview of the terminology used in the development of the digital twin (differences between model, module, application, how they link to other parts of the framework), and gives additional details on the graphical user interface through which the back-end models are used. These descriptions serve to provide context to the remainder of this document, but are not aimed at providing a comprehensive technical overview of the framework code or how to install and set up GEMINI, this will be part of the technical user manual released along with the open-source publication.

### Terminology

Figure 1 shows a schematic overview of the architecture of the GEMINI digital twin, consisting of a number of core layers, the main being the framework layer, which contains the model layer, module layer, and application layer. The differences between these layers are as follows:

- The **model layer** contains all models in the digital twin, these are functions that take an input, process or perform calculations on this input, and return the results of these operations back as their output. This output can then be stored in a database, visualized to the user through the Graphical User Interface, or used as the input to another model (or any combination thereof).
- The **module layer** contains the different modules in the digital twin. A module consists of a specific model calculation or multiple chain models that are executed at a predefined regular interval. For instance, an ESP head module may calculate the pump head every half hour. All modules are connected to a scheduler (see next subsection) that keeps track of time and manages when each asynchronous task should be executed. Module results are stored in a calculation database and can be visualized through the embedded Grafana view to keep track of the calculated values in real time (described in more detail in a later subsection).
- The **application layer** contains all applications in the digital twin. An application consists of one or more models. However, where modules are executed based on a pre-set schedule, the models in an application run offline, and are directly controlled by a user of the digital twin. As such, applications are typically more complex than modules and have dedicated user interfaces through which a person can run the models, experiment with varying with inputs, and visualize their outcomes.

In addition to the above mentioned layers, the digital twin also contains a database layer with various databases in which different types of data are stored, a project layer through which different instances of the digital twin can be managed (e.g. it is possible to have a project for an entire doublet, or a project for just an ESP, or a project for a doublet in one location, and a separate project for a doublet in another location, all still accessible through the same program by the same user), and a graphical user interface. The purpose of the framework layer is to make sure all these different layers can connect and interact with each other.

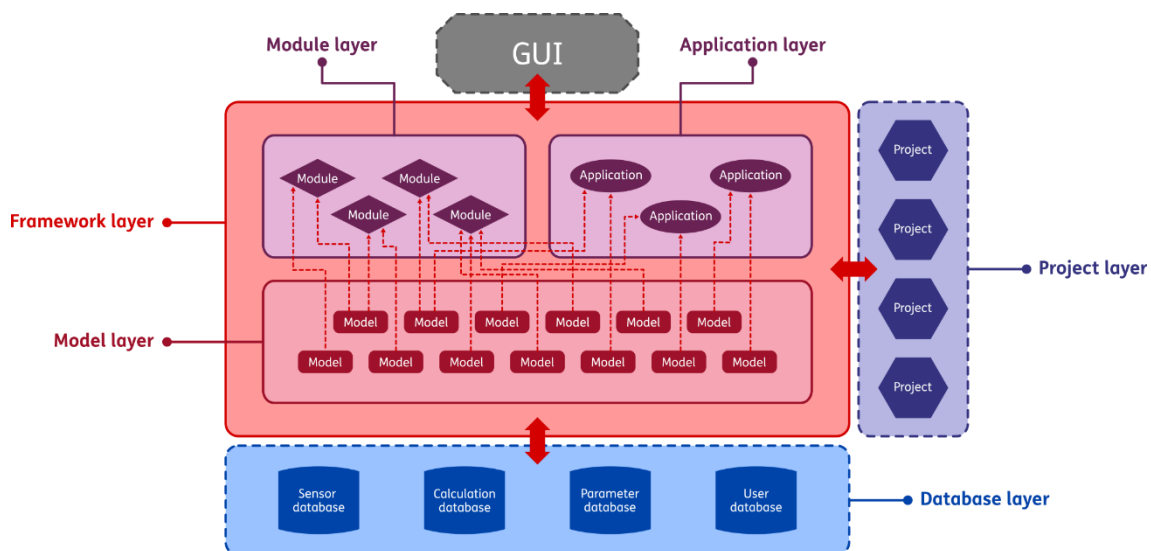


Figure 1 Schematic overview of the architecture of the GEMINI digital twin framework

## Technical architecture

The GEMINI digital twin framework has been developed with its open-source publication in mind. This means that all tools and software packages that GEMINI relies on to fulfill its core functionalities are all also open-source. Figure 2 gives a schematic overview of GEMINI's architecture indicating the software tools used to implement its various functions, these include:

- The **back-end code**. This is the bulk of the GEMINI digital twin and contains the framework, models, modules, and applications, which are all developed within the Python programming language. Through the back-end it is possible to include applications not written in Python (e.g. functional mock-up units, Matlab scripts, other external simulators), although this requires custom code to be written per application, and requires the application to be able to be interacted with through Python code. All new developments for/within GEMINI should ideally be written in Python for optimal interoperability.
- The **front-end code**. The front-end is the part of the digital twin through which a user interacts with all its functionalities. This is often also referred to as the visualization layer or the Graphical User Interface (GUI). The front-end is written in a combination of HTML, CSS, and JavaScript. In particular, GEMINI makes use of the Bootstrap framework<sup>1</sup>.
- The **web server gateway interface**. This is the software package responsible for connecting the front-end to the back-end, allowing the inputs provided and selections made by a user to reach the back-end, and (calculation) outputs coming from the back-end to be available in the front-end. In GEMINI this is done through the Python package Flask<sup>2</sup>.
- The **internal database layer**. In order not to have to interact directly with external databases when reading, viewing, displaying, or performing calculations on plant data (and also prevent accidental overwrites), GEMINI employs a number of internal databases. These databases regularly load in the external data. In addition, these internal databases are also used to store non-sensor data such as documents, system-wide settings, and project specific data. GEMINI uses a variety of databases depending on the type of data to be stored, including MySQL<sup>3</sup>/MongoDB<sup>4</sup> for regular tabular data, InfluxDB<sup>5</sup> for time-series data, and Redis<sup>6</sup> for caching.

<sup>1</sup> <https://getbootstrap.com/>

<sup>2</sup> <https://flask.palletsprojects.com/en/stable/>

<sup>3</sup> <https://www.mysql.com/>

<sup>4</sup> <https://www.mongodb.com/>

<sup>5</sup> <https://www.influxdata.com/>

<sup>6</sup> <https://redis.io/>

- The **external database** connections. While the internal databases are used by GEMINI to safely manage data locally, most of this data, in particular the sensor data, comes from an external source. GEMINI has been developed to allow direct connection to the industry-standard data management system AVEVA Datahub<sup>7</sup>. In addition, GEMINI also allows the user to upload data manually through the use of excel, csv or other file formats. Moreover, there are a few formats planned to be incorporated in future versions of the digital twin.
- The **workflow manager**. The GEMINI digital twin performs certain actions (e.g. performing calculations, retrieving data from external databases) at fixed (user-defined) intervals. In order to keep track of properly schedule these tasks, GEMINI employs the open-source Celery workflow manager<sup>8</sup>.
- The **authenticator**. Within GEMINI, multiple users can work together on different projects. To manage and ensure secure encryption of user accounts and passwords, GEMINI uses the built-in authentication capabilities of Flask together with a MySQL database.
- **External services**. Depending on the need, new functionalities can be written in GEMINI that allow direct interfacing with a variety of external services. Such as, for instance, the Grafana visualization software, and the open-source large language model management platform Ollama<sup>9</sup> (see Deliverable 2.3 of the project).

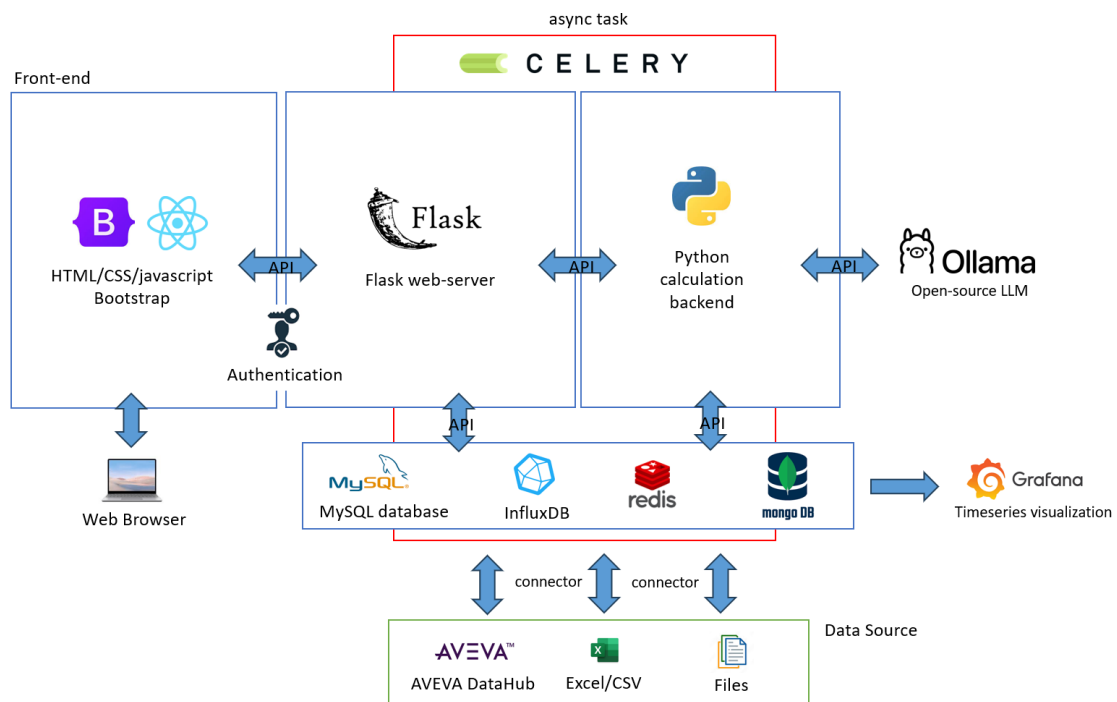


Figure 2 Technical architecture of the GEMINI digital twin.

## User interface

The user interface (sometimes also referred to as the Graphical User Interface or GUI) of the GEMINI digital twin is the primary way through which a user of the digital twin can interact with its various functionalities. The user interface provides a variety of menus and applications through which the user can set up the system, make connections to database(s) containing sensor data, view data, and execute models in order to analyze their system's performance.

When starting the application, after logging in and opening a project, the user is shown the main

<sup>7</sup> <https://www.aveva.com/en/>

<sup>8</sup> <https://docs.celeryq.dev/en/stable/#>

<sup>9</sup> <https://ollama.com/>

dashboard view of the digital twin (Figure 3). The dashboard contains a short overview of the GEMINI digital twin and the Nieuwe Warmte Nu! project in which it was developed. In addition, the dashboard contains a customizable Grafana view (see the Timeseries Viewer section later on) in which the user can display key performance indicators to have an instant overview of the status and performance of their system.

On the left side, the user interface provides a list of all the menus and applications included in the digital twin. As this document focuses on model implementation through modules and applications, it will focus primarily on the functionalities listed under the application field that implement the models adapted or developed within the Nieuwe Warmte Nu! project (from “Production Well Performance” to “Well Schematics”). In addition, as the “Diagram Builder” and “Time Series Viewer” applications have key interactions with the models, modules, and applications running in the back-end of the GEMINI digital twin, they will be briefly discussed in the next two subsections.

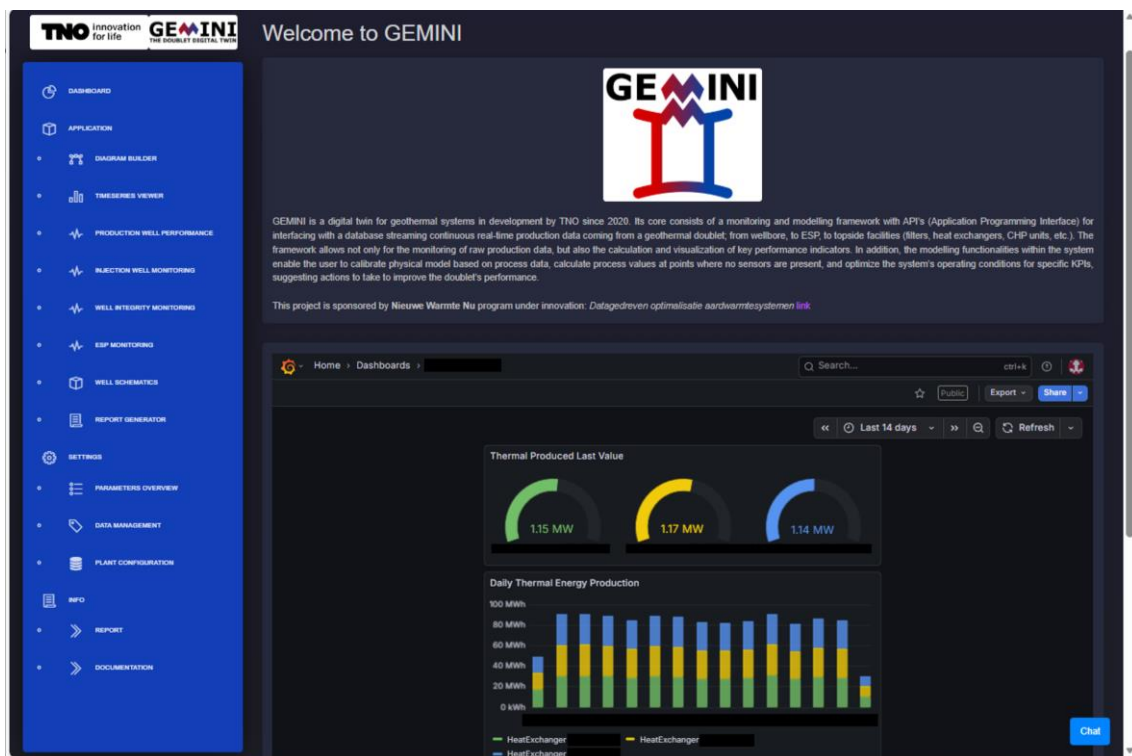


Figure 3 The main view (dashboard) of the GEMINI digital twin user interface.

### Diagram builder

The diagram builder is an essential part of the GEMINI digital twin, as it allows a user to set up the digital twin such that it mirrors the real-world system it is connected to. Figure 4 shows a screenshot of the diagram builder in the GEMINI digital twin with a simple example of a geothermal doublet with its essential (primary side) equipment in place. Through the interactive interface, a user can build up their system by clicking on one of the unit buttons in the bottom of the view, and dragging and dropping them into the right place. The user can then connect inputs from one unit to outputs of another, and vice versa. Each unit corresponds to a typical part of a geothermal system, such as a reservoir, a production or injection well, an ESP, booster pump, heat exchanger, etc.

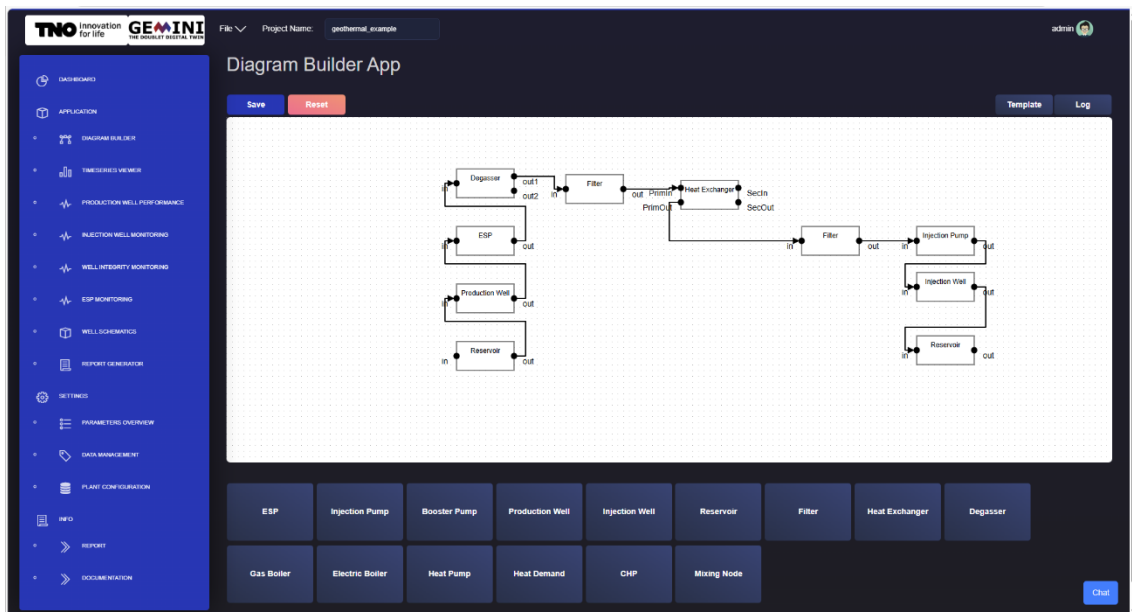


Figure 4 Screenshot of the diagram builder in the GEMINI digital twin graphical user interface

When right-clicking on a unit in the main interface, one can either delete the unit, or open its parameter menu. The parameter menu (Figure 5) allows the user to further set up the specific instance of the unit in question, providing the parameters/property values needed by the models in GEMINI (such as the type of ESP, its number of stages, etc.; or the reservoir pressure/temperature, and so on). Each unit will have a unique set of parameter fields that a user will need to fill in. It is essential that these parameters are provided, as without them the relevant models will not be able to be executed. Once filled in, the parameters will be saved to the current project, and will be used in all future sessions. If needed, the parameters can be updated through the same interface at a later date. GEMINI keeps track of the parameter history so it is always clear when each parameter value was in use by the system.

In addition to setting the units modelling parameters, the parameter menu also allows the user to set which tags (ID's used to identify measured variables coming from the system that collects the sensor data) belong to which variable in a more human-readable format; e.g. measured 'ESP intake pressure [bar]' corresponds to tag "SITE.Channel1A.DeviceB.DB\_Geotherm\_Data.IntakePressure". Since tags are unique to most plants, this helps the framework perform general tasks and calculations using site specific data. Like the parameters, tags can be updated at a later time and GEMINI will keep track of their history.

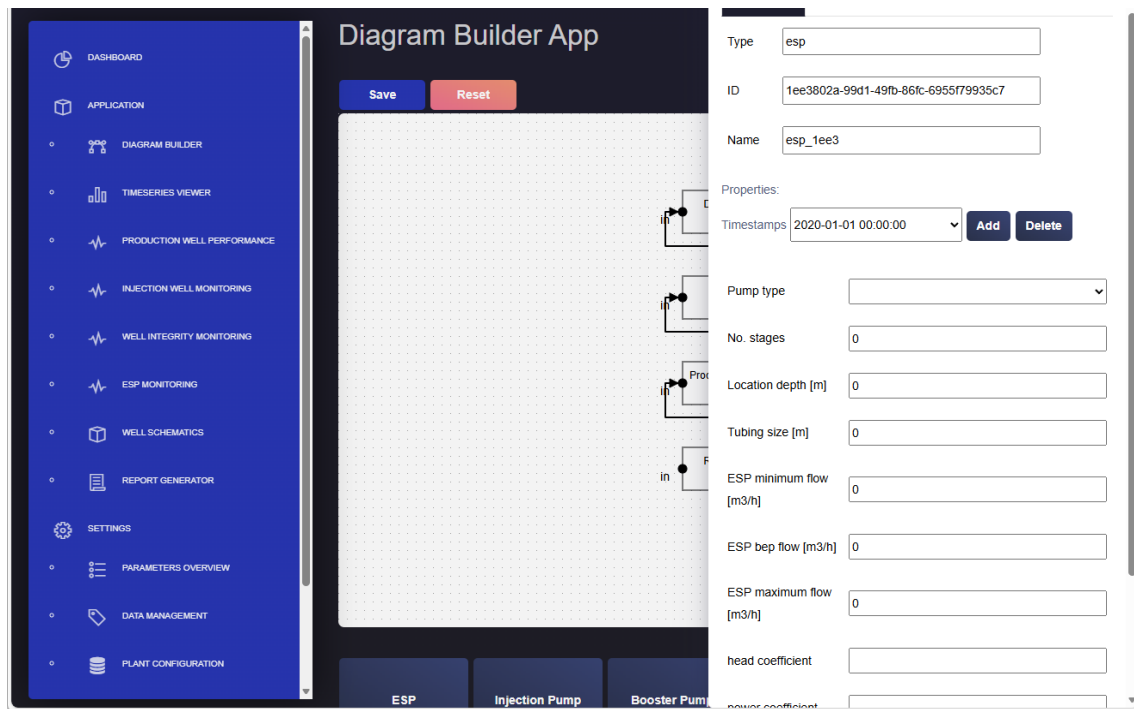


Figure 5 Screenshot of the diagram builder of the GEMINI digital twin with the ESP unit parameter menu open

### Timeseries viewer

The main way through which a user of the GEMINI digital twin interacts with data in the database and module outcomes is by the Timeseries Viewer application. This application embeds the open-source timeseries visualization software Grafana. Grafana connects directly to a timeseries database and has a wide variety of visualization capabilities. It allows a user to define what data they want to display, and how they want to display it. In addition, Grafana has the capability to create so-called 'dashboards', which allows a user to define combinations of multiple plots and save it to their account. At a later stage, this dashboard can then be directly loaded, providing the user with the same view as they defined earlier. Dashboards are a great way to group visualization of variables belonging to a specific unit or subject (e.g. all ESP related variables can be saved to an 'ESP dashboard'). In addition, Grafana allows these dashboards to be exported and imported by other users. As such, users of GEMINI that have worked with Grafana in the past can still access all their dashboards directly from within GEMINI. Furthermore, new dashboards can be created in Grafana directly from GEMINI. A (censored) screenshot of the timeseries viewer is shown in Figure 6.

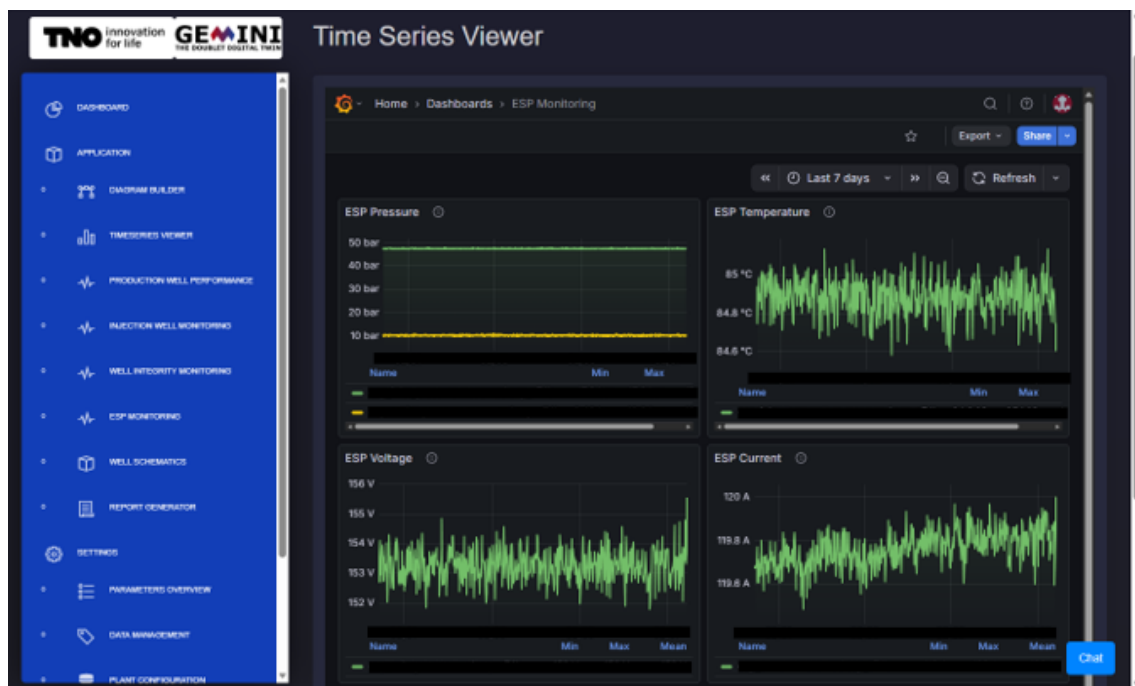


Figure 6 Screenshot of the time series viewer application that allows users to view measured and calculated values in real-time (names and details censored for privacy concerns)

### 3. Basic models

Most of the modules and applications in the GEMINI digital twin depend on fluid properties and pressure-flow calculations. The models used by the GEMINI digital twin to perform these calculations are described in this chapter. The basic models available in the GEMINI digital twin have been developed previously by TNO within internal research projects, and within the NWN! GEMINI project have been adapted to fit within the new model template and overall digital twin framework.

#### Fluid model

Fluid models are foundational for the calculation of flow related variables in the system as they calculate key fluid properties such as density, viscosity, and multi-phase flow fractions based on system operating conditions such as pressure and temperature. GEMINI currently provides constant values for a selection of fluid properties of water at standard pressure and temperature (0 degrees Celsius and 100,000 Pascals). These properties are shown in Table 1. As can be seen, the model provides property data for the gas phase (assumed to be CO<sub>2</sub>) as well. However, by default the model assumes that the gas mass fraction is zero, so by default these values will not be used in subsequent calculations. By updating the parameter of gas mass fraction, the model can also be used to model a CO<sub>2</sub>-water system.

*Table 1 Inputs, parameters, and outputs of the water/CO<sub>2</sub> at standard temperature and pressure model used in GEMINI.*

| Variable                                    | Type   | Unit              | Value (if constant)    |
|---------------------------------------------|--------|-------------------|------------------------|
| <u>Temperature</u>                          | Input  | K                 | -                      |
| <u>Pressure</u>                             | Input  | Pa                | -                      |
| <u>Density of gas phase</u>                 | Output | kg/m <sup>3</sup> | 1.976                  |
| <u>Density of liquid phase</u>              | Output | kg/m <sup>3</sup> | 1000                   |
| <u>Gas mass fraction</u>                    | Output | -                 | 0                      |
| <u>Viscosity of gas phase</u>               | Output | Pas               | 21.29*10 <sup>-6</sup> |
| <u>Viscosity of liquid phase</u>            | Output | Pas               | 0.001                  |
| <u>Heat capacity of gas phase</u>           | Output | J/kg/K            | 819                    |
| <u>Heat capacity of liquid phase</u>        | Output | J/kg/K            | 4217.4                 |
| <u>Thermal conductivity of gas phase</u>    | Output | W/m/K             | 0.0147                 |
| <u>Thermal conductivity of liquid phase</u> | Output | W/m/K             | 1.6                    |
| <u>Surface tension</u>                      | Output | N/m               | 0.0728                 |

In addition, as they are critical properties for the calculation of pressure drop and fluid flow in geothermal systems, GEMINI provides the option of updating the density and viscosity of the fluid based on temperature, pressure, and salinity values using the Batzle-Wang correlations (Batzle & Wang, 1992).

The Batzle-Wang correlation calculates the density of regular water first by using a polynomial relation in pressure and temperature (Batzle & Wang, 1992):

$$\rho_{water} = 1 + 1 * 10^{-6}(-80T - 3.3T^2 + 0.00175T^3 + 489P - 2TP + 0.016T^2P - 1.3 * 10^{-5}T^3P - 0.333P^2 - 0.002TP^2)$$

Which is subsequently used to calculate the brine value using:

$$\rho_{brine} = \rho_{water} + S \left( 0.668 + 0.44S + 1 * 10^{-6} (300P - 2400PS + T(80 + 3T - 3300S - 13P + 47PS)) \right)$$

Where:

- $\rho_{brine}$  (output) is the density of the brine in [kg/m<sup>3</sup>]
- $\rho_{water}$  (intermediate) is the density of water in [kg/m<sup>3</sup>],
- $T$  (input) is the temperature of the brine in [°C],

- $P$  (input) is the pressure in of the brine in [MPa], and
- $S$  (input) is the salinity of the brine in [ppm].

Viscosity is directly calculated using the following relation in salinity and temperature (Batzle & Wang, 1992):

$$\eta = 0.1 + 0.333 * S + (1.65 + 91.9 * S^3) * e^{-\left(0.42 * (S^{0.8} - 0.17)^2 + 0.045\right) * T^{0.8}}$$

Where  $\eta$  is the viscosity in Pas.

All functions were derived from experimental data as described in (Batzle & Wang, 1992). It should be noted that Batzle and Wang mention that this relation has been established for brines consisting containing primarily sodium-chloride, and it can vary significantly for other types of brines. In addition, while they do not explicitly mention the lower and upper limits of temperature, pressure, and salinity for their correlations, Batzle and Wang provide plots in their publications that range include the following bounds:

- Temperature between 20 and 350 degrees Celsius.
- Pressure between 0.1 and 100 megapascal.
- Salinity between 0 and 300,000 parts per million.

Table 2 provides an overview of the input and output variables of the PVT brine model as implemented within GEMINI.

*Table 2 Inputs, parameters, and outputs of the PVT brine Batzle-Wang correlation (Batzle & Wang, 1992).*

| Variable           | Type   | Unit              | Value (if constant) |
|--------------------|--------|-------------------|---------------------|
| <u>Temperature</u> | Input  | K                 | -                   |
| <u>Pressure</u>    | Input  | Pa                | -                   |
| <u>Salinity</u>    | Input  | ppm               | -                   |
| <u>Density</u>     | Output | kg/m <sup>3</sup> | -                   |
| <u>Viscosity</u>   | Output | Pas               | -                   |

## Pressure drop models

Pressure drop is essential to calculate in the simulation of geothermal system, as it has a major impact on production rates, as well as energy demands of pump systems. The total pressure drop along a length of pipe is a combination of two contributions, one as a result of gravity (zero in case the pipe is oriented fully horizontally), and one as a result of friction of the fluid with the pipe wall.

Of these two contributions, that of gravity is the simplest to calculate based on density, the length of the pipe, the angle of the pipe, and the gravitational constant:

$$\Delta P_{grav} = \rho * g * L * \sin \theta$$

Where:

- $\Delta P_{grav}$  (output) is the pressure drop due to gravity in [Pa],
- $\rho$  (input) is the density of fluid in [kg/m<sup>3</sup>],
- $g$  (constant) is the acceleration due to gravity in [m/s<sup>2</sup>],
- $L$  (input) is the length of the pipe in [m], and
- $\theta$  (input) is the inclination angle of the pipe in [rad]

When dealing with two-phase gas-liquid flow, the calculation of gravitational pressure drop stays the same. However, the density should be calculated as a gas-liquid fraction weighted sum of the gas and liquid densities:

$$\rho_{mixture} = (H_l) * \rho_l + (1 - H_l) * \rho_g$$

Where:

- $\rho_{mixture}$  (intermediate) is the combined two-phase density in [kg/m<sup>3</sup>],
- $\rho_l$  (input) is the density of the fluid phase in [kg/m<sup>3</sup>],
- $\rho_g$  (input) is the density of the gas phase in [kg/m<sup>3</sup>], and
- $H_l$  (input) is the fraction of the liquid phase (liquid hold-up) in [-]

On the other hand, the pressure drop due to friction is a lot more complicated, depending not only on the fluid density and pipe length, but also the pipe diameter, fluid velocity, and most notably the friction factor, which needs to be calculated using one of a myriad of possible correlations. In its most general form, frictional pressure drop is calculated through the Darcy-Weissbach equation (Swamee & Jain, 1976):

$$\Delta P_{fric} = f * \rho * \frac{L}{D} * \frac{v^2}{2}$$

Where:

- $\Delta P_{fric}$  (output) is the pressure drop due to friction in [Pa],
- $f$  (input) is the friction factor in [-],
- $\rho$  (input) is the density of fluid in [kg/m<sup>3</sup>] (replaced by the mixture density in case of two-phase flow),
- $L$  (input) is the length of the pipe in [m],
- $D$  (input) is the hydraulic diameter of the pipe in [m], and
- $v$  (input) is the velocity of the fluid flow in [m/s]

While most of these parameters are readily available, the friction factor  $f$  needs to be calculated with an additional equation that often depends on the roughness of the pipe and the Reynolds number of the flow through the pipe. However, as the behavior of the friction factor is rather complex and is flow regime dependent, there are many different correlations that can be used for it, varying greatly in complexity. In addition, depending on whether the pressure drop is calculated for single-phase or two-phase fluid flow, the nature of the friction factor correlation changes as well.

The GEMINI digital twin provides two options for calculating the friction factor, one for single-phase flow, and one for two-phase gas-liquid flow. These are:

- The Swamee-Jain single-phase correlation (Swamee & Jain, 1976).
- The Beggs and Brill two-phase correlation (Beggs & Brill, 1973).

As the flow in geothermal system is always assumed to be turbulent due to the large pipe diameters and high flowrates, all of these correlations are for turbulent flows. In the next subsections, each of the listed correlations is discussed in more detail.

### **Swamee-Jain correlation**

The Swamee-Jain correlation for the friction factor used in the Darcy-Weissbach equation. It is an explicit approximation of the more complex implicit Colebrook-White correlation (Colebrook & White, 1937), and depends primarily on the pipe roughness, its diameter, and the Reynolds number (Swamee & Jain, 1976):

$$f = \frac{0.25}{\left( \log \left( \frac{\epsilon}{3.7D} + \frac{5.74}{Re^{0.9}} \right) \right)^2}$$

Where:

- $f$  (output) is the friction factor in [-],
- $\epsilon$  (input) is the pipe roughness in [m],
- $D$  (input) is the pipe diameter in [m], and
- $Re$  (input) is the Reynolds number of the fluid flow in [-]

The Reynolds number for internal pipe flow is calculated as follows:

$$Re = \frac{vD\rho}{\eta}$$

Where:

- $Re$  (intermediate) is the Reynolds number of the fluid flow in [-],
- $v$  (input) is the (superficial) velocity of the fluid flow in [m/s],
- $D$  (input) is the pipe diameter in [m], and
- $\eta$  (input) is the viscosity of the fluid in [Pas]

Here the superficial fluid velocity is the velocity of the liquid phase assuming it is the only phase present, and is calculated by dividing the volume flow through the pipe by its cross-sectional area. The Swamee-Jain correlation is accurate to within 1% of the Colebrook-White equation for roughness to diameter ratios ( $\frac{\epsilon}{D}$ ) within the range of  $10^{-6}$  to  $10^{-2}$ , and is valid within Reynolds number ranges of 5000 to  $10^8$ .

In GEMINI, the Swamee-Jain correlation is the default correlation used, and is often also referred to simply as the standard Darcy-Weissbach correlation. Table 3 provides an overview of all the inputs, parameters/constants, and outputs of the Swamee-Jain friction factor correlation model.

*Table 3 Inputs, parameters, and outputs of the Swamee-Jain (Darcy-Weissbach) friction factor correlation model.*

| Variable                                | Type     | Unit              | Value (if constant) |
|-----------------------------------------|----------|-------------------|---------------------|
| <u>Superficial liquid velocity</u>      | Input    | m/s               | -                   |
| <u>Liquid density</u>                   | Input    | kg/m <sup>3</sup> | -                   |
| <u>Liquid viscosity</u>                 | Input    | Pas               | -                   |
| <u>Pipe (section) inclination angle</u> | Input    | rad               | -                   |
| <u>Pipe (section) diameter</u>          | Input    | m                 | -                   |
| <u>Pipe (section) roughness</u>         | Input    | m                 | -                   |
| <u>Pipe (section) length</u>            | Input    | m                 | -                   |
| <u>Acceleration due to gravity</u>      | Constant | m/s <sup>2</sup>  | 9.81                |
| <u>Frictional pressure drop</u>         | Output   | Pa                | -                   |
| <u>Gravitational pressure drop</u>      | Output   | Pa                | -                   |

### **Beggs and Brill correlation**

The Beggs and Brill correlation is used to calculate the friction factor of two-phase gas-liquid flow. Since it is a rather complex process to calculate the Beggs and Brill calculation, the full workflow is not provided in this text for brevity sake. Instead, this section will cover the major details and concepts on which the correlation relies. For the full details, the reader is referred to the original publication: (Beggs & Brill, 1973).

The Beggs and Brill correlation aims to calculate the liquid hold up (the fraction of the pipe taken up by the liquid phase at a given instant) based on the two-phase flow regime of the fluids in the pipe in a horizontal orientation. Once known, this hold-up is corrected for the angle of the pipe and used to calculate the friction factor (as well as combined liquid-gas density).

Based on the above, the first step in the Beggs and Brill correlation is to estimate the flow regime, which can be one of the following:

- Segregated<sup>10</sup>
- Intermittent

<sup>10</sup> It should be noted that while for vertical flows the segregated flow regime does not exist, in the current implementation of the Beggs and Brill correlation this distinction is not explicitly made (all inclinations are treated the same), and thus it is technically possible for a vertical segregated flow regime to exist.

- Distributed
- Transition

These regimes are separated by four flow regime boundaries that depend on the Froude number ( $\frac{v^2}{g \cdot D}$ ) of the flow and the liquid flux ratio (the ratio between the superficial liquid flow velocity, and the sum of the liquid and gas flow velocities). Figure 7 shows a plot of the four flow regimes as functions of the Froude number ( $N_{Fr}$ ) and liquid flux ratio ( $C_L$ ). By calculating the lines L1-L4 using expressions provided in (Beggs & Brill, 1973), the flow regime can be determined without the use of the plot in Figure 7.

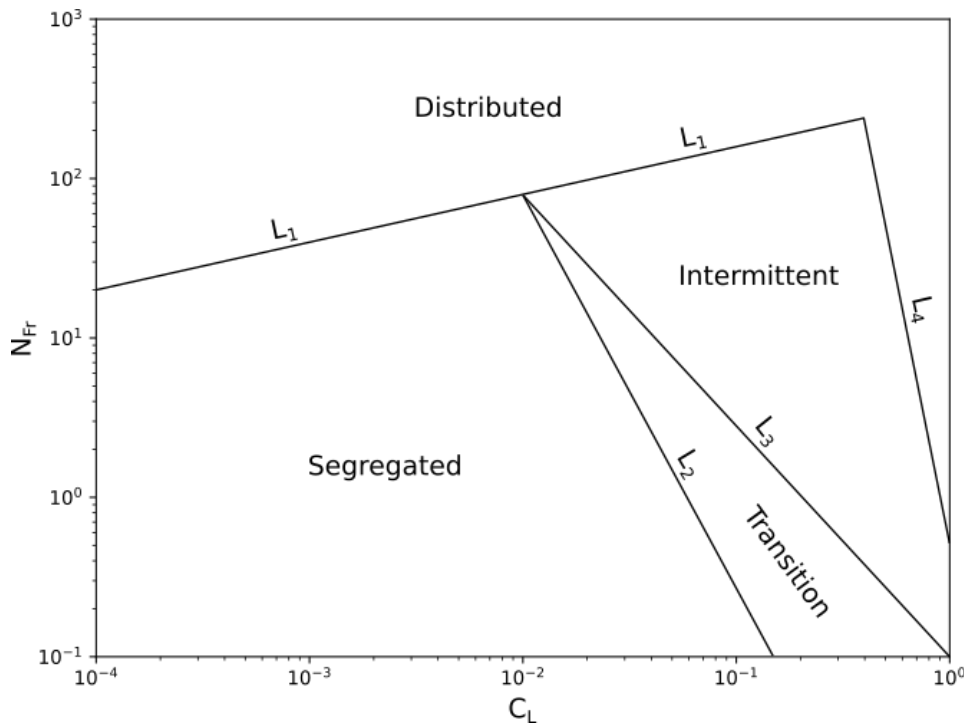


Figure 7 Diagram showing the boundaries of the four flow regimes considered by the Beggs and Brill two-phase flow friction correlation. Adapted from (Beggs and Brill - whitson wiki, 2026).

Once the flow regime is known, the horizontal liquid hold-up ratio can be calculated using a simple relation:

$$H_{l,0} = A * C_L^\alpha * N_{Fr}^\beta$$

Where:

- $H_{l,0}$  (output) is the liquid hold-up for a horizontal pipe in [-],
- $C_L$  (input) is the liquid flux ratio in [-],
- $N_{Fr}$  (input) is the Froude number in [-], and
- $A, \alpha, \beta$  are coefficients that depend on the flow regime and are given in (Beggs & Brill, 1973).

With the horizontal liquid hold-up known, it needs to be corrected for the inclination angle of the pipe. This is done by calculating a correction factor that, like the liquid hold-up itself, depends on the flow regime:

$$\psi = 1 + B \left( \sin(1.8 * \theta) - \frac{1}{3} \sin^3 \theta \right)$$

Where:

- $\psi$  (output) is the liquid hold-up inclination correction factor in [-],
- $\theta$  (input) is the inclination angle of the pipe in [rad], and
- $B$  (input) is a coefficient calculated based on the liquid flux ratio, diameter, Froude number, and the dimensionless liquid velocity as well as a number of coefficients depending on the flow regime,

provided in (Beggs & Brill, 1973).

When the correction factor has been calculated, the adjusted liquid hold-up is calculated by multiplying it with the already known horizontal hold-up.

The above process is valid for the segregated, intermittent, and distributed flow regimes. In the case of the transition flow regime, the liquid hold-up is calculated as a weighted average of the intermittent and distributed flow regime solutions:

$$H_{l,trans} = x * H_{l,seg} + (1 - x) * H_{l,inter}$$

With  $x$  being the fractional distance in the transition regime, calculated as:

$$x = \frac{L_3 - N_{Fr}}{L_3 - L_2}$$

Where  $N_{Fr}$  is the Froude number, and  $L_3$  and  $L_2$  are the flow regime boundaries from Figure 7, whose equations are provided in (Beggs & Brill, 1973).

Finally, the two-phase friction factor including slip ( $f_s$ ) is calculated as a correction on the base Darcy friction factor ( $f_D$ ):

$$f_s = \exp(S) * f_D$$

With  $S$  given by:

$$S = \ln(2.2y - 1.2) \text{ if } y \text{ is between } 1 \text{ and } 1.2, \text{ and}$$

$$S = \frac{\ln(y)}{-0.0523 + 3.182 \ln(y) - 0.8725 \ln(y)^2 + 0.01853 \ln(y)^4}, \text{ otherwise}$$

Where  $y$  is the fraction of the liquid flux ratio and the square of the angle-corrected liquid hold-up ( $y = \frac{C_L}{H_L^2}$ ). In the GEMINI digital twin, the original Darcy friction factor before correction ( $f_D$ ) is calculated using the single-phase Swamee-Jain correlation.

Table 4 gives an overview of all the inputs, parameters/constants, and outputs of the Beggs and Brill model as implemented in GEMINI. While complex to calculate, the Beggs and Brill correlation is widely used, and based on the tests ( $n=584$ ) performed by Beggs and Brill is on average accurate to around 1% when used to calculate the pressure gradient (Beggs & Brill, 1973).

*Table 4 Inputs, parameter, and outputs of the Beggs and Brill two-phase friction factor correlation*

| Variable                                | Type  | Unit              | Value (if constant)                            |
|-----------------------------------------|-------|-------------------|------------------------------------------------|
| <u>Superficial gas velocity</u>         | Input | m/s               | -                                              |
| <u>Superficial liquid velocity</u>      | Input | m/s               | -                                              |
| <u>Density of the gas phase</u>         | Input | kg/m <sup>3</sup> | -                                              |
| <u>Density of the liquid phase</u>      | Input | kg/m <sup>3</sup> | -                                              |
| <u>Viscosity of the gas phase</u>       | Input | Pas               | -                                              |
| <u>Viscosity of the liquid phase</u>    | Input | Pas               | Constant value 0.001 in current implementation |
| <u>Surface tension</u>                  | Input | N/m               | -                                              |
| <u>Pipe (section) inclination angle</u> | Input | rad               | -                                              |
| <u>Pipe (section) diameter</u>          | Input | m                 | -                                              |
| <u>Pipe (section) roughness</u>         | Input | m                 | -                                              |
| <u>Pipe (section) length</u>            | Input | m                 | -                                              |

|                                    |          |                  |      |
|------------------------------------|----------|------------------|------|
| <u>Acceleration due to gravity</u> | Constant | m/s <sup>2</sup> | 9.81 |
| <u>Frictional pressure drop</u>    | Output   | Pa               | -    |
| <u>Gravitational pressure drop</u> | Output   | Pa               | -    |

### **Temperature drop model**

When calculating the overall pressure drop along a long section of pipeline (e.g. the productivity or injection wells), the effects of changing temperature due to heat exchange with the ambient environment cannot be disregarded. Therefore, GEMINI contains a model that calculates this temperature drop (or increase when injecting) using the simple heat flux equation:

$$Q = U * A_{tube} * (T_{in} - T_{ambient})$$

Where:

- $Q$  (output) is the heat flux between well and ambient environment in [W],
- $U$  (input) is the heat transfer coefficient in [W/m<sup>2</sup>K],
- $A_{tube}$  (input) is the surface area of the pipe (section) in [m<sup>2</sup>],
- $T_{in}$  (input) is the temperature of the fluid at the pipe inlet in [K], and
- $T_{ambient}$  (input) is the temperature of the outside ambient environment (formation/soil) in [K]

With the heat flux known, the temperature drop over the pipe (section) can be calculated as:

$$\Delta T = \frac{Q}{\dot{m}_{tot} * C_{p,mix}}$$

Where:

- $\Delta T$  (output) is the temperature drop in the pipe section in [K],
- $Q$  (input) is the heat flux between well and ambient environment in [W],
- $\dot{m}_{tot}$  (input) is the total mass flow of the fluid, calculated by summing the liquid and gas mass flowrates in [kg/s], and
- $C_{p,mix}$  (input) is the combined gas-liquid heat capacity calculated as the gas/liquid fractional weighted sum of the heat capacities of the gas and liquid phase in [J/kg/K]

Table 5 provides an overview of all the inputs and the output of the temperature drop model used within GEMINI.

*Table 5 Inputs, parameters, and outputs of the temperature drop model.*

| Variable                                                                      | Type   | Unit                | Value (if constant) |
|-------------------------------------------------------------------------------|--------|---------------------|---------------------|
| <u>Inlet temperature of pipe (section)</u>                                    | Input  | K                   | -                   |
| <u>Heat transfer coefficient between pipe section and ambient environment</u> | Input  | W/m <sup>2</sup> /K | -                   |
| <u>Mas flowrate of the liquid phase</u>                                       | Input  | kg/s                | -                   |
| <u>Mas flowrate of the gas phase</u>                                          | Input  | kg/s                | -                   |
| <u>Heat capacity of gas phase</u>                                             | Input  | J/kg/K              | -                   |
| <u>Heat capacity of liquid phase</u>                                          | Input  | J/kg/K              | -                   |
| <u>Pipe (section) surface area</u>                                            | Input  | m <sup>2</sup>      | -                   |
| <u>Ambient temperature</u>                                                    | Input  | K                   | -                   |
| <u>Temperature drop over pipe (section)</u>                                   | Output | K                   | -                   |

### **Well pressure drop calculation workflow**

The above models for calculating the pressure and temperature drops are all brought together in a model that calculates the temperature and pressure along the length of the production or injection wells.

This is done by dividing the entire length of the well into multiple sections that describe the trajectory of the well in more detail. The well trajectory is defined by the user when setting up a new project by

uploading an excel sheet that describes it. Table 6 provides some dummy example data to show how the well trajectory is typically defined.

*Table 6 Example well trajectory dummy data*

| True vertical depth [m] | Measured depth [m] | Inner diameter [m] | Material | Roughness [m] |
|-------------------------|--------------------|--------------------|----------|---------------|
| 0                       | 0                  | 0.1778             | Steel    | 0.000025      |
| 500                     | 500                | 0.1778             | Steel    | 0.000025      |
| 750                     | 750                | 0.273              | Steel    | 0.00003       |
| 1200                    | 1250               | 0.273              | Steel    | 0.000035      |
| 1500                    | 1600               | 0.273              | Steel    | 0.000035      |

Using the information of the well trajectory, the pressure drop model divides the total well length into individual sections as defined by the rows in the well trajectory table. The inclination angle of the pipe section can be calculated from the true vertical depth and measured depth. Here, a positive value corresponds to inclination, while a negative value corresponds to declination of the pipe. In addition, the script also extracts the pipe section diameter, length, material, and roughness. From these parameters, the model calculates the cross-sectional area and area along the pipe's length. The heat transfer coefficient  $U$  is assumed to be constant at 10 W/m<sup>2</sup>/K. Based on whether the well is a production or injection well, the flow direction is assumed to be upwards or downwards. The ambient temperature is also assumed to be constant along the entire well trajectory, and is set by the user when setting up the digital twin system.

The main pressure drop calculation starts by initiating a loop over all the sections defined in the well trajectory. For each section, the following calculation steps are taken:

1. The PVT model is used to retrieve the gas and liquid densities, viscosities, heat capacities, heat conductivities, surface tension, and gas mass fraction for the pressure and temperature in the current section. By default, the flow is assumed to be single-phase liquid. This can be updated in the fluid property model as described in fluid model section.
2. If there is two-phase flow, the gas mass fraction is used to calculate the mixture density, which in turn is used to determine the total mass flowrate using the input flowrate, and the individual gas and liquid mass flowrates.
3. If the gas mass fraction is zero, the model automatically select the Swamee-Jain friction factor correlation. If the gas mass fraction is non-zero, the flow is two-phase, and the model automatically select the Beggs and Brill correlation to be used.
4. The model calculates the superficial liquid and gas (if relevant) velocities by dividing their respective mass flowrates by their densities and the cross-sectional pipe area.
5. With the superficial velocities, densities, viscosities, pipe section angle, pipe section diameter, roughness, and pipe section length (and surface tension in case of two-phase flow), the frictional and gravitational pressure drops for the current pipe section of the well are calculated. This uses the friction correlation as determined in Step 3 and as described in the earlier subsections.
6. Using the temperature drop model described earlier, the temperature loss across the current pipe section is calculated based on the fixed heat transfer coefficient, the area along the pipe section's wall, the gas/liquid mass flowrates and their respective heat capacities, as well as the constant ambient temperature.
7. Based on the pressure and temperature drop calculations, the overall pressure and temperature along the well trajectory are updated. If the flow direction is up (production), the pressure drop components and temperature are *subtracted* from the total pressure and temperature, while for a downwards flow direction (injection), they are *added* to the total pressure and temperature. For a production well, the initial pressure and temperature are defined by the user as the reservoir pressure and temperature. In case of an injection well, the initial pressure and temperature come from the outlet of the last unit before injection begins (almost always the injection pump).
8. In addition, the total pressure value is updated by adding a linear correction ( $P_{corr} = a * P + b$ ) with two fixed correction factors  $a$  and  $b$ . These correction factors are based on the calibration done in the ESP monitoring application and are further described in Section 5.

The steps above are repeated until all sections have been iterated through. Table 7 gives an overview of all inputs, parameters, and outputs of the pressure and temperature drop model as implemented in the GEMINI digital twin.

*Table 7 Inputs, parameters, and outputs of the pressure and temperature drop model.*

| Variable                                                                   | Type      | Unit                | Value (if constant)                                               |
|----------------------------------------------------------------------------|-----------|---------------------|-------------------------------------------------------------------|
| <u>Flow direction in pipe/well</u>                                         | Input     | -                   | "up" or "down"                                                    |
| <u>Pressure at inlet of pipe/well</u>                                      | Input     | Pa                  | -                                                                 |
| <u>Temperature inlet of pipe/well</u>                                      | Input     | K                   | -                                                                 |
| <u>Flowrate in pipe/well</u>                                               | Input     | m <sup>3</sup>      | -                                                                 |
| <u>Ambient temperature of the soil</u>                                     | Input     | K                   | -                                                                 |
| <u>Lengths of pipe sections</u>                                            | Parameter | m                   | -                                                                 |
| <u>Inclination angles of pipe sections</u>                                 | Parameter | rad                 | -                                                                 |
| <u>Diameters of pipe sections</u>                                          | Parameter | m                   | -                                                                 |
| <u>Roughness values of pipe sections</u>                                   | Parameter | m                   | -                                                                 |
| <u>Fraction factor correlation to be used</u>                              | Parameter | -                   | Number corresponding to single- or two-phase correlation equation |
| <u>Pressure correction factors</u>                                         | Parameter | -                   | -                                                                 |
| <u>Heat transfer coefficient between pipe/well and ambient environment</u> | Constant  | W/m <sup>2</sup> /K | 10                                                                |
| <u>Pressure at outlet of pipe/well</u>                                     | Output    | Pa                  | -                                                                 |
| <u>Temperature at outlet of pipe/well</u>                                  | Output    | K                   | -                                                                 |
| <u>Total frictional pressure drop over pipe/well</u>                       | Output    | Pa                  | -                                                                 |
| <u>Total gravitational pressure drop over pipe/well</u>                    | Output    | Pa                  | -                                                                 |
| <u>Pressure at each pipe section outlet</u>                                | Output    | Pa                  | -                                                                 |
| <u>Temperature at each pipe section outlet</u>                             | Output    | K                   | -                                                                 |

The pressure drop calculations are primarily used in the productivity well performance application (Section 4) to calculate the pressure from the reservoir to the ESP inlet, and from the ESP outlet to the production wellhead.

## 4. Production well performance

The Production well performance application provides monitoring and analysis tools for production wells in geothermal plants. It includes Inflow Performance Relationship (IPR), Vertical Lift Performance (VLP), and nodal analysis when Electrical Submersible Pump (ESP) is in place to predict the well operating point (flow rate and pressures) to support design and optimization of production strategies.

### Models

The application uses three model components:

- The **IPR** (Inflow Performance Relationship) relates reservoir pressure and flowing bottomhole pressure to production rate from the reservoir.
- The **VLP** (Vertical Lift Performance) relates flowing bottomhole pressure and any pressure node in the well to flow rate along the wellbore (pressure drop from wellhead to bottomhole or from ESP intake to bottomhole), using single-phase or two-phase flow correlations.
- The **nodal analysis** finds the operating point where the IPR and VLP curves intersect. That is where the wellbore pressure from VLP matches the reservoir deliverability from IPR and gives the equilibrium flow rate and associated pressures.

### Inflow performance relation

The IPR describes the well flowing bottomhole pressure ( $P_{wf}$ ) as a function of production rate ( $Q$ ). It represents reservoir deliverability and is essential for nodal analysis and production optimization. A typical IPR graph is illustrated in Figure 8 (R. Octaviano, S. Dussi, H. de Zwart, P. Shoeibi Omrani, V. van Pul-Verboom, K. Elewaut, B. van Schravendijk, 2022).

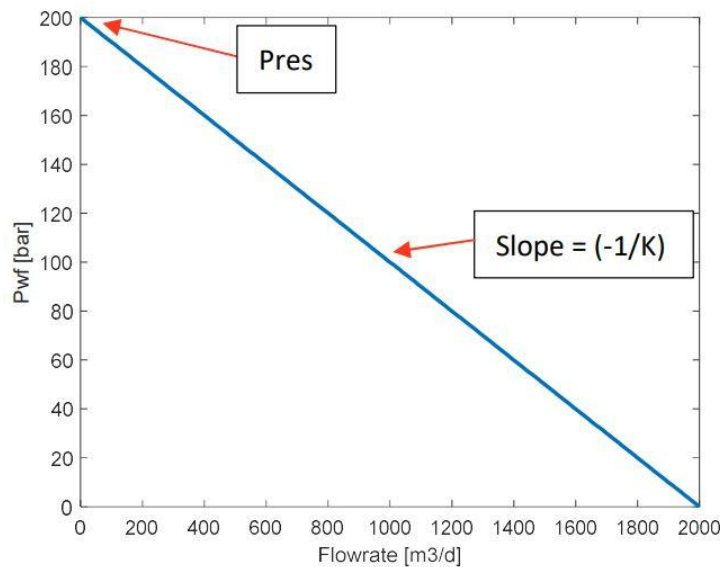


Figure 8 Example Inflow Performance Relationship graph.

For a production reservoir, the model uses a linear productivity index ( $K$ , also known as PI). For each flow rate ( $Q$ ), the IPR model returns the bottomhole pressure that would be required to deliver that rate from the reservoir (Ahmed, 2019).

$$P_{wf} = P_{res} - \frac{Q}{K}$$

with the productivity index defined as:

$$K = \frac{Q}{P_{res} - P_{wf}}$$

Where:

- $P_{wf}$  (output) is the flowing bottomhole pressure in [Pa],
- $P_{res}$  (parameter) is the average reservoir pressure in [Pa],

- Q (input) is the production flow rate in [m<sup>3</sup>/s], and
- K (parameter) is the productivity index in [m<sup>3</sup>/(s.Pa)].

Table 8 provides an overview of the input variables, parameters, and output variables of the IPR model as implemented in the GEMINI digital twin.

*Table 8 Inputs, parameters, and outputs of the IPR model*

| Variable                           | Type      | Unit                   | Value (if constant)  |
|------------------------------------|-----------|------------------------|----------------------|
| <u>Flow rate</u>                   | Input     | m <sup>3</sup> /s      | -                    |
| <u>Average reservoir pressure</u>  | Parameter | Pa                     | -                    |
| <u>Productivity index (K)</u>      | Parameter | m <sup>3</sup> /(s.Pa) | -                    |
| <u>Type</u>                        | Parameter | -                      | production_reservoir |
| <u>Flowing bottomhole pressure</u> | Output    | Pa                     | -                    |

The model assumes a linear relationship between rate and pressure drop. It is appropriate for single-phase liquid flow and for reservoirs where this approximation is valid (e.g. undersaturated conditions). Quasi-steady-state is assumed; transient effects are not modelled. The formulation is for a single well; interference from other wells is not included.

The model is most useful for comparing different operating conditions, screening flow rates, and performing nodal analysis when combined with VLP.

### **Model validation**

The IPR has been validated through unit testing against known IPR data. The test verifies for the average reservoir pressure of 300 bar, productivity index of 5 m<sup>3</sup>/(h.bar), and flow rate of 100 m<sup>3</sup>/h, the flowing bottomhole pressure is 200 bar.

### **Vertical lift performance**

The VLP describes the bottomhole pressure as a function of flow rate along the wellbore. It includes both friction and gravity and depends on well trajectory, tubing size, fluid properties, and flow regime (single-phase or two-phase).

In the production well performance application, the well is split into two segments when an ESP is present:

- VLP1: From wellhead down to the ESP (discharge side); here the boundary condition is wellhead pressure.
- VLP2: From ESP intake down to the bottomhole; here the boundary condition is the ESP intake pressure.

The schematic below, Figure 9, illustrates a typical pressure profile across a geothermal production well equipped with an ESP:

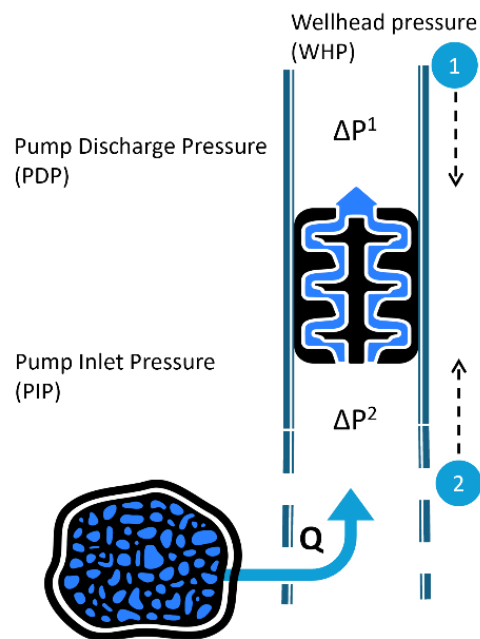


Figure 9 The schematic of a typical pressure profile across a geothermal production well equipped with an ESP.

For each segment, pressure drop is computed with the same underlying model of pressure drop, using the appropriate boundary conditions and direction (“up” for the production path from bottomhole to the wellhead and “down” for injection path from wellhead to bottomhole).

The total pressure change along a segment is the sum of frictional and gravitational contributions as follows:

$$\Delta P_{total} = \Delta P_{friction} + \Delta P_{gravity}$$

The pressure drop calculation has been extensively explained in Section 3.

When an ESP is installed, the application uses the ESP performance to compute pump head, power, and efficiency as a function of flow rate and frequency. The pump head is used to link the two VLP segments:

- VLP1: wellhead pressure to discharge pressure (at ESP outlet)
- ESP: discharge pressure – pump head = intake pressure
- VLP2: intake pressure to bottomhole pressure

A full description of the ESP model is given in Section 5.

### Nodal analysis

Nodal analysis combines IPR and VLP (and ESP when present) to find the operating point: the flow rate at which the bottomhole pressure from the wellbore (VLP2 + ESP + VLP1) matches the bottomhole pressure from the reservoir (IPR). This point is shown in the plot of Figure 10, and is the point where the well naturally operates for given boundary conditions (reservoir pressure, wellhead pressure, ESP frequency, etc.).

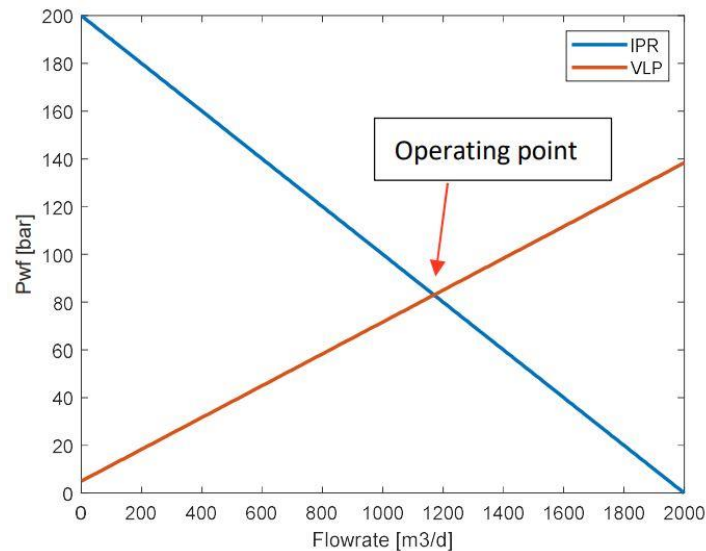


Figure 10 Example of operating point between IPR and VLP.

As described in Figure 11, for a range of flow rates ( $Q$ ) the:

- The IPR computes the bottomhole pressure from reservoir side ( $P_{wf,res}$ ),
- The VLP (and ESP), starting from wellhead pressure (and applying ESP head between the two segments), computes the bottomhole pressure from wellbore side ( $P_{wf,well}$ )

The operating point is the flow rate that minimizes the squared difference between the two bottomhole pressures:

$$\min_Q (P_{wf,res} - P_{wf,well})^2$$

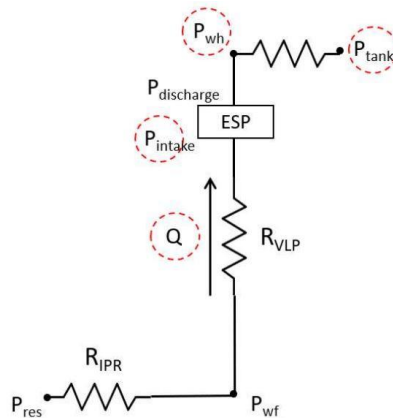


Figure 11 Schematic of well-reservoir nodal system

## Implementation

The production well performance application is implemented as a web-based interface integrated into the GEMINI platform. Users can select a production well, set reservoir and well parameters (and ESP parameters if applicable), and run the calculation to obtain IPR, VLP, and the operating point.

In the implementation, a discrete set of flow rates is used (e.g. from 0.8 times to 1.1 times the ESP operating range). The flow at which  $P_{wf,res} - P_{wf,well}$  is minimal is taken as the solution, together with the corresponding pressures, pump head, power, and efficiency. The application provides a plot (Figure 12) showing:

- The IPR: flowing bottomhole pressure vs flow rate (reservoir deliverability).
- The VLP: bottomhole pressure vs flow rate (wellbore performance). When an ESP is used, pressure

- profiles (discharge, intake, bottomhole from well, and reservoir) can be shown vs flow rate.
- The nodal analysis result: the intersection of IPR and VLP shows the operating point.

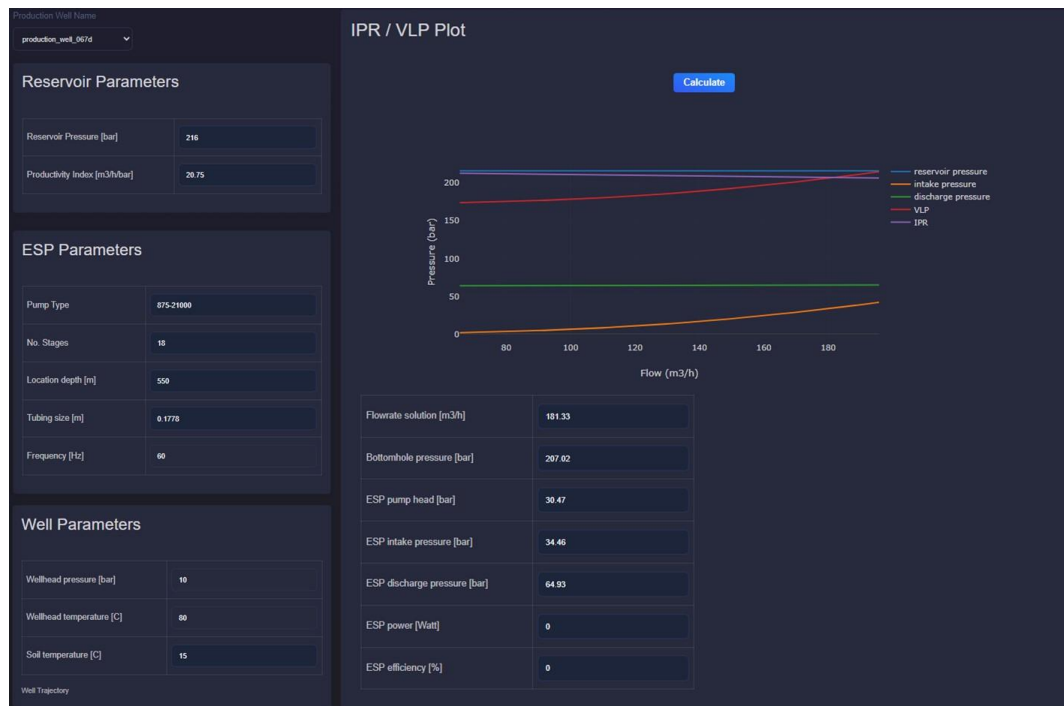


Figure 12 Example of production well performance application.

## 5. ESP monitoring

The ESP (Electrical Submersible Pump) application provides comprehensive monitoring, calibration, and failure prediction capabilities for ESPs installed in geothermal production wells. ESPs are critical components in geothermal systems, installed in production wells to provide additional lift when reservoir pressure is insufficient to bring the fluid to the surface. They increase pressure between the pump intake (inlet) and discharge (outlet), that allows production from deeper or lower-pressure reservoirs.

The ESP monitoring application provides three functionalities to the user:

- Monitoring of ESP based on the real-time sensor data coming from the physical ESP and production data.
- Calibration and calculation of theoretical pump head and outlet pressure, as well as comparison of these values against measured data to enable anomaly detection.
- Prediction of future ESP failure probabilities using data-driven models (a preliminary model).

The models used for the calculations and predictions of the latter two functionalities will be explained in the next section in more detail. The monitoring functionality will be explained in more detail in the section discussing the details of implementation of the ESP application.

### Models used in the ESP application

The application integrates an ESP performance model for monitoring ESP performance. This is a physics-based model that calculates pump head, power consumption, and efficiency using polynomial correlations derived from manufacturer performance curves (R. Octaviano, S. Dussi, H. de Zwart, P. Shoeibi Omrani, V. van Pul-Verboom, K. Elewaut, B. van Schravendijk, 2022). In addition, a model calibration workflow to tune the ESP curves with the production data and update it based on the latest production status is incorporated into the application.

#### *ESP model*

The ESP performance model calculates key pump performance characteristics (head, power consumption, and efficiency) based on operating conditions (flow rate and frequency). This model is essential for understanding pump behavior, optimizing operations, and comparing actual performance against manufacturer specifications. In addition, the model can be used to predict values for variables not measured in the physical system in order to still allow operators to gain insights on otherwise unmeasured parts of the ESP system.

The ESP model uses polynomial correlations that describe the relationship between flow rate and pump head, and power consumption. These correlations are pump-specific and are typically derived from manufacturer performance pump curves. The model applies pump affinity laws to scale these correlations based on operating frequency.

#### **Pump head calculation**

The pump head is calculated using a fifth-order polynomial correlation that relates flow rate to head at a reference frequency (60 Hz). The correlation is then scaled using pump affinity laws to calculate for different operating frequencies. Affinity laws for pumps describes how performance changes with rotational speed. For a given pump and fluid, the flow rate is proportional to speed, head is proportional to speed squared, and power is proportional to speed cubed. This means small speed increases can significantly raise power demand, which is critical when optimizing ESP operation and motor loading.

First, if the pump curve is provided in US oilfield units, the flow rate is converted from SI units (m<sup>3</sup>/s) to US oilfield units (barrels per day, bbl/d):

$$Q_{bbl} = Q_{m3s} * 543439.650564$$

The pump head at the operating frequency is then calculated using (Octaviano, et al., 2022):

$$H_{ft} = N_{stages} * \left(\frac{f}{60}\right)^2 * (C_0 + C_1 Q_{bbl} + C_2 Q_{bbl}^2 + C_3 Q_{bbl}^3 + C_4 Q_{bbl}^4 + C_5 Q_{bbl}^5)$$

$$H = H_{ft} * 2988.30167$$

Where:

- H (output) is the pump head in [Pa],
- $N_{stages}$  (parameter) is the number of pump stages [-],
- f (input) is the pump operating frequency in [Hz],
- $H_{ft}$  (intermediate) is the head in [ft],
- $Q_{bbl}$  (intermediate) is the flow rate in [bbl/d],
- $Q_{m3s}$  (input) is the flow rate in [m<sup>3</sup>/s], and
- $C_0, C_1, C_2, C_3, C_4, C_5$  (parameters) are the head correlation coefficients [-].

### Pump power calculation

The pump power consumption is calculated using a similar fifth-order polynomial correlation, also scaled by frequency. The pump power at the operating frequency is then calculated using the following equation and based on affinity laws:

$$P_{BHP} = N_{stages} * \left(\frac{f}{60}\right)^3 * (B_0 + B_1 Q_{bbl} + B_2 Q_{bbl}^2 + B_3 Q_{bbl}^3 + B_4 Q_{bbl}^4 + B_5 Q_{bbl}^5)$$

$$P_W = P_{BHP} \times 745.7$$

Where:

- P (output) is the pump power consumption in [W],
- $N_{stages}$  (parameter) is the number of pump stages [-],
- f (input) is the pump operating frequency in [Hz],
- $Q_{bbl}$  (intermediate) is the flow rate in [bbl/d],
- $Q_{m3s}$  (input) is the flow rate in [m<sup>3</sup>/s], and
- $B_0, B_1, B_2, B_3, B_4, B_5$  (parameters) are the power correlation coefficients [-].

### Pump efficiency calculation

The pump efficiency is calculated from the flow rate, head, and power using the fundamental relationship between hydraulic power and electrical power:

$$\eta = 100 * \left(\frac{Q_{bbl}}{135773}\right) * \left(\frac{H}{P}\right) * \left(\frac{745.7}{2988.30167}\right)$$

Where:

- $\eta$  (output) is the pump efficiency in [%],
- $Q_{bbl}$  (intermediate) is the flow rate in [bbl/d],
- H (intermediate) is the pump head in [Pa], and
- P (intermediate) is the pump power consumption in [W].

If the calculated pump power is less than 0.1 W, the efficiency is set to zero to avoid division by zero or unrealistic efficiency values at very low power conditions.

Table 9 provides an overview of the input variables, parameters, and output variables of the ESP performance model as implemented in the GEMINI digital twin.

Table 9 Inputs, parameters, and outputs of the ESP performance model

| Variable                   | Type  | Unit              | Value (if constant) |
|----------------------------|-------|-------------------|---------------------|
| Flow rate through the pump | Input | m <sup>3</sup> /s | -                   |
| Pump operating frequency   | Input | Hz                | -                   |

|                                                 |           |    |   |
|-------------------------------------------------|-----------|----|---|
| <u>Number of pump stages</u>                    | Parameter | -  | - |
| <u>Head correlation coefficients</u>            | Parameter | -  | - |
| <u>Power correlation coefficients</u>           | Parameter | -  | - |
| <u>Total head developed by the pump</u>         | Output    | Pa | - |
| <u>Electrical power consumption of the pump</u> | Output    | W  | - |
| <u>Pump efficiency</u>                          | Output    | %  | - |

The ESP performance model is based on polynomial correlations derived from manufacturer performance pump curves. As such, the accuracy of the model depends on:

- The quality of the original performance pump curve data
- The accuracy of the polynomial fitting procedure
- The operating conditions being within the range of the original performance curves

In addition, the model currently assumes:

- Single-phase liquid flow (no gas handling)
- Constant fluid properties within the ESP (density and viscosity)
- Ideal pump affinity law behavior (no mechanical losses or efficiency variations with frequency), otherwise it needs to be calibrated by the time

The model is applicable to standard ESP configurations operating in geothermal brine production systems. The correlations are typically valid for flow rates within the pump's operating range (between minimum and maximum recommended flow rates) and frequencies between approximately 30 Hz and 70 Hz.

### Model validation

The ESP performance model has been validated through unit testing against known pump performance data. The test includes:

- A standard calculation: It validates that the model produces correct head, power, and efficiency values for a known pump configuration (a known pump model, 12 stages) at standard operating conditions (60 Hz, 200 m<sup>3</sup>/h flow rate). The test verifies that the pump head is 23.37 bar (within 0.01 bar tolerance), the pump power is 183.89 kW (within 0.01 kW tolerance), and the pump efficiency is 70.53% (within 0.01% tolerance).
- A special case for missing power coefficient: it validates model behavior at low power conditions, ensuring that efficiency is correctly set to zero when power consumption is negligible.

## Implementation

The ESP Performance application is implemented as a web-based interface integrated into the GEMINI platform. The application is organized into three main functional areas: "Monitoring", "Calibration", and "Prediction". As the latter is out-of-scope for this document, only the first two will be discussed in this report.

### *The Monitoring tab*

The Monitoring tab provides real-time visualization of ESP performance and operational data, allowing users to compare actual pump performance against manufacturer specifications. It provides two main plots, one in which the recent history of the measured ESP pump head and flowrate are plotted on the ESP's pump curve, and one in which the recent history of the measured flowrate and ESP frequency.

The main visualization shows the ESP pump curve from the manufacturer, plotted as head versus flow rate (shown in Figure 13). Theoretical frequency lines (typically 30, 40, 50, and 60 Hz) are displayed as "Theoretical Frequency" curves. Real-time operational data is overlaid on the pump curve, with data points color-coded by time to show temporal trends.

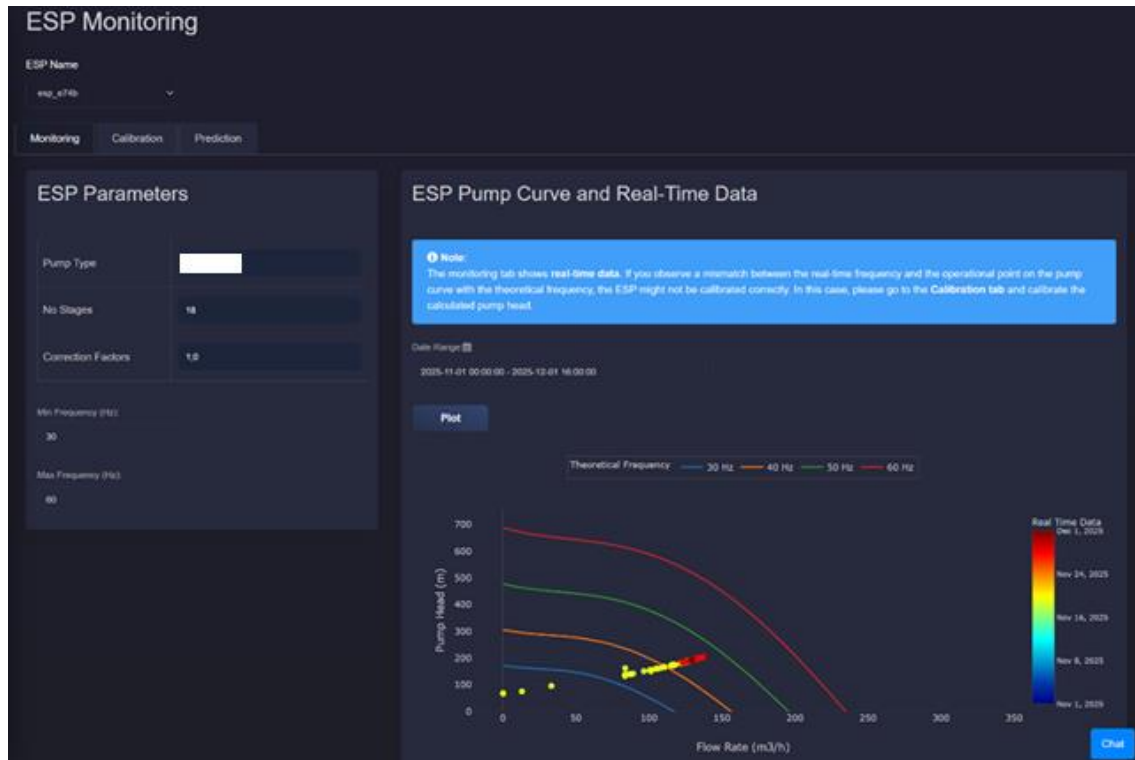


Figure 13 ESP Pump Curve and Real-Time Data.

Since there is usually no discharge pressure sensor in ESP systems, the pump head is estimated using:

- Inlet pressure: Measured directly by a downhole sensor.
- Upper pressure difference ( $\Delta P^1$ ): Calculated using the VLP (Vertical Lift Performance, explained in detailed in the section 4) model from the top of the ESP to the wellhead.

From these values, the actual pressure increase provided by the pump is estimated ( $P_{whf} - \Delta P^1 - P_{inlet}$ ), giving the real-time pump head plotted with the flow rate on top of the manufacturer pump curve.

In addition to the pump curve plot, a time-series plot displays the measured flow rate and frequency over the selected date range. This helps users identify operational patterns and potential issues with pump performance.

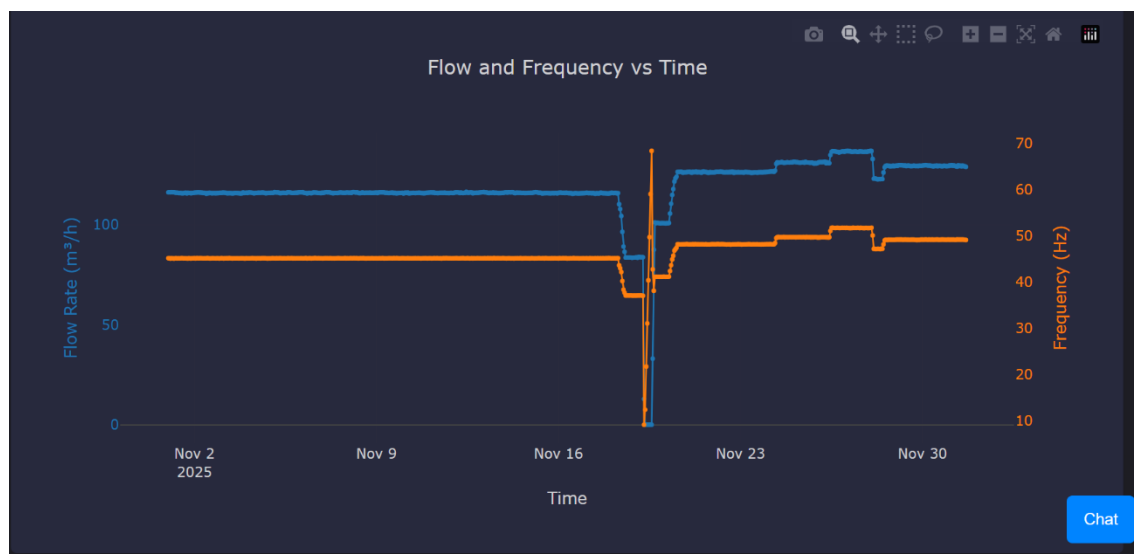


Figure 14 Flow rate and Frequency Plot.

The application is used by performing the following steps:

1. Select the date range for analysis using the start and end time inputs.
2. The application automatically retrieves measured data (flow rate, frequency, inlet pressure) and calculated values (VLP head, theoretical head).
3. Review the pump curve plot to compare actual performance against theoretical curves.
4. If there is a mismatch between the real-time frequency and the operational point on the pump curve with the theoretical frequency, proceed to the Calibration tab.

### ***The Calibration tab***

The Calibration tab enables users to calibrate the ESP model by aligning calculated values with theoretical expectations. The calibration performs a linear fit, for simplicity and robustness, between the calculated VLP head and the theoretical head from the pump curve. The goal is to match the “calculated VLP head” to the “theoretical head” that comes from the pump curve:

$$H_{calibrated} = a * H_{VLP} + b$$

Where:

- $H_{calibrated}$  (output) is the calibrated head in [bar],
- $H_{VLP}$  (input) is the head calculated via VLP in [bar],
- $a$  (parameter) is the calibration slope coefficient [-], and
- $b$  (parameter) is the calibration intercept coefficient [bar]

By clicking "Run Calibration", the application performs a linear regression (least squares fit) for the selected time period. The calibration coefficients  $a$  and  $b$  are displayed in the calibration window and can be saved in the Parameters Overview so the calibration is applied to future ESP performance evaluations. If over time the calculated and theoretical head start to misalign again, it is recommended to repeat the calibration process including the most recently measured data.

In addition, the calibration process step itself, the Calibration tab also shows time-based comparisons between real-time measurements and expected values from ESP models. If a calibration of the model has been performed, it will display both the calculations made before calibration and the updated values after calibration.



Figure 15 comparison plots for the calibrated and measured head, outlet pressure of ESP and inlet pressure of the ESP.

The main comparison plot contains a number of subplots, the most critical plot of which is the head comparison plot at the top, which is used in the previously described calibration step. It includes the following variables:

- VLP Head: calculated using pressure drop from the top of the ESP to the wellhead (since no discharge sensor is available) and measured intake pressure.
- Theoretical Head: calculated from the manufacturer pump curve using current flow and frequency.
- Calibrated Head: VLP head adjusted using calibration coefficients (if applied) to better match the theoretical head.

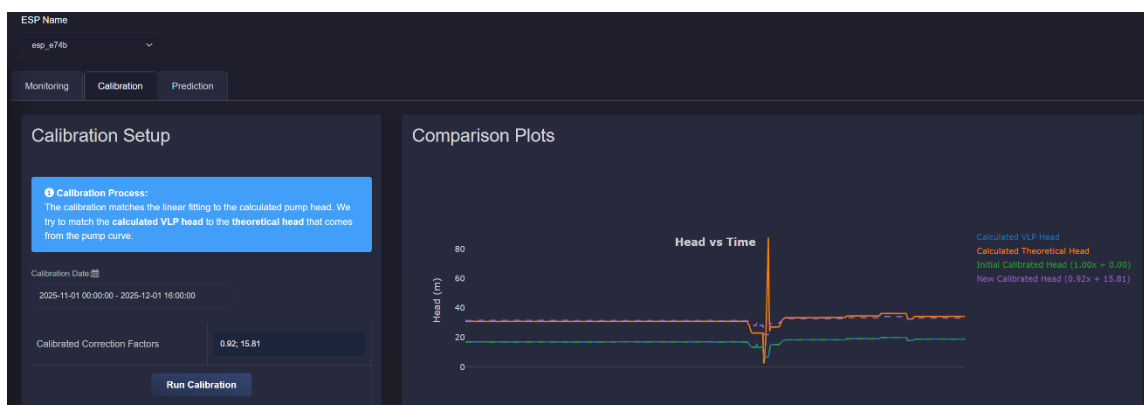


Figure 16 ESP Head calculation comparison before and after the model calibration.

If no calibration is applied, default values are used with  $a = 1$  and  $b = 0$ . This helps users see the initial mismatch between measured and expected pump behavior.

Below the head comparison, the outlet Pressure Comparison plot is shown. As no discharge pressure sensor was in place for the system the developments were tested on, the plot currently shows the

following variables:

- VLP-based Outlet Pressure: calculated from the pressure drop above the ESP and wellhead pressure
- Theoretical Outlet Pressure: calculated using the measured inlet pressure and theoretical pump head

Finally, the bottom subplot shows the inlet pressure comparison, this compares:

- Measured Inlet Pressure: the measured pressure value from the ESP sensor at the pump intake.
- Calculated Inlet Pressure: calculated from the IPR (Inflow Performance Relationship, using reservoir pressure and flow rate) and VLP (from reservoir to pump location, using bottomhole pressure and pressure drop in the lower stage of the ESP,  $\Delta P^2$ ). IPR and VLP calculations are explained in details in Section 4.

These comparisons act as diagnostic tools to check consistency between measurements and expected values. Deviations in head, outlet, or inlet pressures may indicate uncalibrated models, measurement errors, or operational issues.

Calibration is done using the following steps:

1. Select the calibration time period using the calibration start and end time inputs.
2. Click "Run Calibration" to perform the linear regression.
3. Review the calibration coefficients (a and b) displayed in the results.
4. Check the comparison plots to assess the quality of the calibration.
5. If satisfied, save the calibration coefficients in the Parameters Overview for future use.

## 6. Well Integrity Management System

The WIMS (Well Integrity management system) application provides integrity monitoring and analysis for geothermal production and injection wells. Well integrity is critical for safe and reliable operation; it depends on barrier elements monitoring so that wells stay within design limits and anomalies are detected before they lead to failure. A Well Integrity Management System (WIMS) is a structured framework that ensures the safety, reliability, and environmental integrity of wells throughout their entire lifecycle, from design and construction to operation, suspension, and abandonment. In the Netherlands, WIMS are based on the ISO 16530-1 standard (Well Integrity – Life Cycle Governance) and are mandatory for geothermal operators.

Continuous, precise monitoring remains essential, enabling operators to track corrosion patterns, evaluate mitigation measures, and intervene before problems escalate. The WIMS approach manages these risks by integrating inspection and flow data to prioritize monitoring and maintenance.

The Well Integrity Monitoring application provides three main capabilities:

- Monitoring of well integrity via the WIMS panel.
- Multi-Finger Caliper (MFC) log processing and corrosion rates calculation/calibration.
- Prediction of remaining well life and recommendation on the next logging date.

### Models

The application integrates a modeling approaches based on direct measurement-based corrosion assessment using multi-finger caliper (and potentially acoustic and/or magnetic downhole logs, and optionally corrosion coupons in a side-stream loop). Logs are processed joint-by-joint: mean, max and min internal diameter (or wall thickness) are computed per tubular joint and compared to nominal dimensions or prior logs to quantify wall loss and penetration; corrosion rate is then derived from this data. This provides a baseline at (or before) production start and field-validated data for model calibration and for detecting general or localized corrosion over time.

### Corrosion model

The direct corrosion rate is derived from logs and it is done in two stages: (1) process each caliper log joint-by-joint and (2) compute corrosion rate between two states (baseline vs first log, or consecutive logs). All diameters are in inches unless noted; time is in days; rates are in mm/year; calliper channels name should match (D01, D02, etc.) pattern.

### Log processing

For each tubular joint, the raw log is sliced to that joint's depth interval using the well tally data, i.e.: top measured depth (MD) - Bottom measured depth (MD). Over the joint depth and all fingers, the minimum, maximum and mean diameter are recorded. The maximum penetration (MP) % (worst spot) is calculated based on the given equation:

$$MP = 100 * \frac{D_{max} - ID_{nom}}{OD_{nom} - ID_{nom}}$$

Where:

- MP (output) is the maximum penetration [%],
- $D_{max}$  (input) is maximum measured diameter [inch], and
- $ID_{nom}$  and  $OD_{nom}$  (inputs) are nominal inner and outer diameters [inch].

The circumferential wall loss (CWL) is calculated based on the given equation:

$$CWL = \frac{100}{N} * \left( \sum_{fingers} \frac{D^2 - ID_{nom}^2}{OD_{nom}^2 - ID_{nom}^2} \right)$$

Where:

- CWL (output) is the circumferential wall loss [%],
- $D$  (input) is finger measured diameter [inch],
- $ID_{nom}$  and  $OD_{nom}$  (inputs) are nominal inner and outer diameters [inch], and
- $N$  (input) is the number of calliper fingers [-].

Finally, the remaining wall thickness is calculated as follows:

$$\Delta H = OD_{nom} - D_{max}$$

Where:

- $\Delta H$  (output) is the remaining wall thickness [inch],
- $D_{max}$  (input) is maximum measured diameter [inch], and
- $OD_{nom}$  (input) is the nominal outer diameters [inch].

These values are stored per joint in the “Processed log” (e.g. Mean. ID, Min. ID, Max. ID [inch], Max. Pen. [%], Max. Loss [%], Remaining wall thickness [inch]).

### Corrosion rate (CR) calculation

Processed logs are sorted by date and compared either to the nominal condition at a user-defined baseline date (single log scenario):

$$CR = \frac{(ID_{baseline} - ID_{log}) * 365}{\Delta t}$$

Where:

- CR (output) is the corrosion rate in [mm/year],
- $ID_{baseline}$  (input) is the nominal inner diameter [mm],
- $ID_{log}$  (input) is the logs mean ID for the joint [mm], and
- $\Delta t$  (input) is the time difference between first log date and baseline date [days].

Alternatively the CR can be calculated to each consecutive pair [previous log → current log] (two or more logs scenario):

$$CR = \frac{(ID_{prev} - ID_{curr}) * 365}{\Delta t}$$

Where:

- CR (output) is the corrosion rate in [mm/year],
- $ID_{prev}$  (input) is the previous logs mean ID for the joint [mm],
- $ID_{curr}$  (input) is the most recent logs mean ID for the joint [mm], and
- $\Delta t$  (input) is the time difference between most recent log date and the log date before it [days].

## Implementation

The WIMS application is implemented as a web-based interface integrated into the GEMINI platform through two sub-applications: the Well Schematic application and the Well Integrity Monitoring application. The Well Schematic is a single-input panel that provides multiple schematic components for generating a realistic well representation, which is subsequently used by the integrity monitoring application.

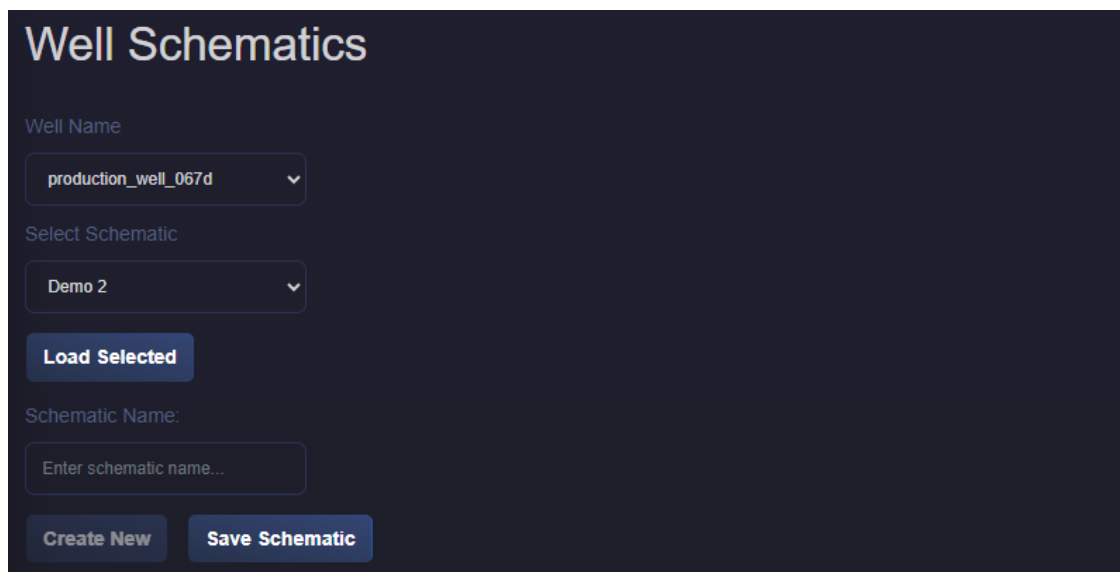
### Well schematic application

The Well Schematics application is used to create, edit, and visualize detailed wellbore schematic diagrams for well integrity. It lets the user define the well configuration (tubulars, fluids, cements, packers, plugs, screens, wellhead, and Xmas tree) and compare the resulting diagram with the intended design. The main interface has two parts: a Well Schematics Input form and a Well Schematic Output area. The form is organized into a Current Units list and tabbed sections: General, Tubulars, Fluids, Cements, Packers, Plugs, Screens, Wellhead, and Xmas Tree. The schematic output shows a depth-based cross-section of the well. The diagram is generated on demand from the current configuration and returned as

an image.

The well schematics application is used as follows:

1. Select the well using the Well Name dropdown (well list is loaded from the selected project).
2. Create a new schematic or load an existing one (Figure 17).
  - Create New: Enter a schematic name, click Create New, then choose a template (Simple Well, Standard Well, Double Skin, or Create from Scratch). The form is filled with the template or left empty.
  - Load existing: Select a saved schematic from the Select Schematic dropdown and click Load Selected to load it into the form.
3. Define or edit units (Figure 18).
  - Create New Unit: Click Create New Unit, fill the Tubulars tab (type, name, depths, OD/ID, optional openhole, draw shoe, hanger seal; for tubing, optional ESP). Add Fluids, Cements, Packers, Plugs, or Screens in their tabs. Adjust General, Wellhead, and Xmas Tree if needed, then click Save Unit.
  - Edit unit: Select a unit in the Current Units list, click Edit Selected Unit, change fields and sub-elements, then use Save Changes, Delete Unit, or Cancel Edit.
4. Preview the diagram by clicking Generate Schematic. The Well Schematic Output card shows the diagram; the application sends the current configuration to the backend and displays the returned image.
5. Save the schematic by entering a Schematic Name and clicking Save Schematic to store it on the server for the selected well.



The screenshot shows the 'Well Schematics' application interface. At the top, the title 'Well Schematics' is displayed in a large, bold, white font. Below the title, there are several input fields and buttons. The first section is labeled 'Well Name' and contains a dropdown menu with the selected value 'production\_well\_067d'. The second section is labeled 'Select Schematic' and contains a dropdown menu with the selected value 'Demo 2'. Below these dropdowns is a blue button labeled 'Load Selected'. The third section is labeled 'Schematic Name:' and contains a text input field with the placeholder text 'Enter schematic name...'. At the bottom of the form are two blue buttons: 'Create New' and 'Save Schematic'.

Figure 17 Schematics Load/Save panel.

Figure 18 Schematics component selection and its data tab.

## Well integrity monitoring application

The Well Integrity Monitoring application provides integrated tools for monitoring well integrity in geothermal and similar wells. It combines caliper log processing and visualization and Well Barrier Envelope (WBE) tracking in a single workflow, enabling comparison of the actual well condition (from caliper logs) with barrier status and risk, and supporting decisions on when remaining wall thickness may approach a limit or when maintenance or inspection should be scheduled.

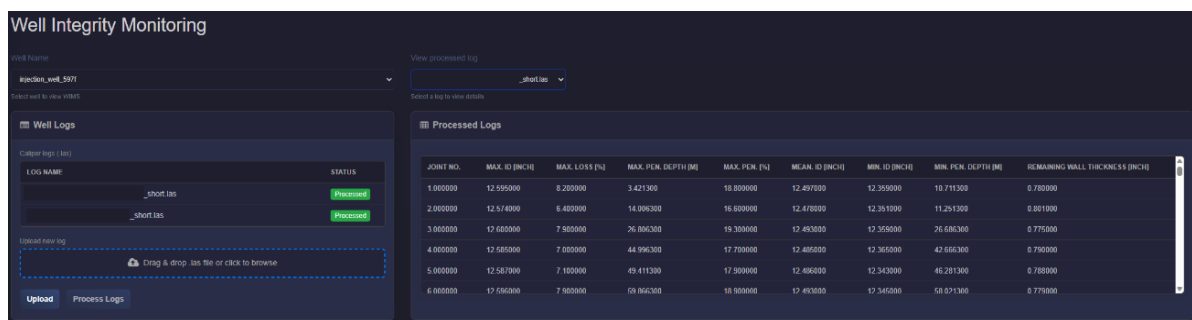
The interface is organized into three sections as shown in Figure 19, Figure 20, and Figure 21. The upper section comprises a well log management area (left), where caliper logs in LAS format can be uploaded and processed, and a results area (right), where a processed log is selected and per-joint outputs are displayed (e.g. joint identifier, penetration, and remaining wall thickness). The Well Integrity Monitoring System (WIMS) panel is shown when the selected well has at least one stored schematic. The user selects a schematic in the panel header; the main view then displays the well schematic together with subpanels for overall integrity status (last update and status: failed, not verified, or verified), the Well Barrier Envelope (WBE) with primary and secondary barrier elements (element, qualification, monitoring, status, remarks), and WBE risk (failure mode, effect, risk indices, action plan, response time, and operation during failure).

Processed logs that have an assigned date are used in chronological order. For the interval from the baseline date to the first log, the corrosion rate (mm/year) is computed as the change in inner diameter (nominal ID from the well tally minus minimum ID from that log), expressed in mm, divided by the elapsed time in days and scaled to an annual rate. For each subsequent interval between two log dates, the rate is based on the change in mean ID between the previous and current log over the interval, again scaled to mm/year. Remaining wall thickness at each log date is taken as the difference between outer diameter from the tally and minimum ID from that log, converted to mm. When a minimum acceptable remaining thickness is specified, the time (in days) until that thickness is reached is estimated per joint by linear extrapolation from the most recent corrosion rate and the most recent remaining thickness. Joints already at or below the minimum are reported as zero days; joints with zero or undefined rate are left blank. The resulting table reports, per joint: joint number, corrosion rate for each time interval, remaining thickness at each log date, and (when configured) estimated remaining days to the minimum thickness.

The well integrity monitoring application is used through the following steps:

1. Select the well using the Well Name dropdown (well list is loaded from the selected project). The Well Logs card and WIMS / Forecasting panels appear for that well.
2. Upload and process caliper logs (Figure 19).  
In the Well Logs card (left): upload .las caliper log files (drag-and-drop or Upload). Click Process

- Logs to run processing. Processed logs are listed with status Processed; select one in View processed log (right) to see the Processed Logs table (per-joint ID, penetration, remaining thickness).
- Use the well schematic.  
Ensure the well has a schematic created in the Well Schematics application and a well tally in Well Parameters. When the selected well has at least one saved schematic, the WIMS Panel is shown.
  - Configure and use the WIMS panel (Figure 20).  
In the WIMS card header, select a saved schematic; optionally click Save panel to store your configuration. The schematic image is displayed (with remaining-thickness overlay when a processed log is selected). Then use the subcards:
    - Overall Integrity status – Set Last update date; use the legend (Failed / Not verified / Verified) to interpret status.
    - Well Barrier Envelope (WBE) — Click Add element; choose Primary or Secondary table, add from schematic or custom, and fill Qualification, Monitoring, Status, Remarks. Click a barrier row to edit or delete. Save panel to store.
    - WBE Risk— Click Add risk; fill Failure mode, Effect, Risk (L, E, RF), Action Plan, Response time (months), Operate during failure. Click a risk row to edit or delete. Save panel to store.
  - Run corrosion extrapolation calculations (Figure 21).  
In the Forecasting Panel: set Baseline date and a date for each processed log in Log and Baseline Dates, then click Save dates. Set Minimum remaining thickness [mm] in Corrosion limits and click Save. Click Calculate to compute corrosion rate and remaining days to minimum thickness. Review the Corrosion table (joint-wise corrosion rates, remaining thickness per log date, remaining days to min. thickness).



The screenshot shows the 'Well Integrity Monitoring' application. On the left, there's a sidebar with 'Well Logs' and a 'Processed Logs' section. The main area displays a table of processed logs. The table has columns for Joint No., Max. ID (inches), Max. Loss (%), Max. Pen. Depth (in), Max. Pen. (%), Mean ID (inches), Min. ID (inches), Min. Pen. Depth (in), and Remaining Wall Thickness (inches). The data shows six logs with varying penetration and remaining thickness values.

| JOINT NO. | MAX. ID (INCH) | MAX. LOSS (%) | MAX. PEN. DEPTH (IN) | MAX. PEN. (%) | MEAN ID (INCH) | MIN. ID (INCH) | MIN. PEN. DEPTH (IN) | REMAINING WALL THICKNESS (INCH) |
|-----------|----------------|---------------|----------------------|---------------|----------------|----------------|----------------------|---------------------------------|
| 1.000000  | 12.595000      | 8.200000      | 3.421300             | 18.800000     | 12.497000      | 12.350000      | 10.711300            | 0.780000                        |
| 2.000000  | 12.514000      | 6.400000      | 14.096300            | 16.800000     | 12.478000      | 12.351000      | 11.251300            | 0.801000                        |
| 3.000000  | 17.000000      | 7.900000      | 26.806300            | 19.300000     | 12.493000      | 12.350000      | 26.686300            | 0.775000                        |
| 4.000000  | 12.585000      | 7.000000      | 44.996300            | 17.700000     | 12.486000      | 12.365000      | 42.666300            | 0.790000                        |
| 5.000000  | 12.587000      | 7.100000      | 49.411300            | 17.900000     | 12.486000      | 12.343000      | 46.281300            | 0.788000                        |
| 6.000000  | 17.000000      | 7.900000      | 68.806300            | 18.100000     | 12.493000      | 12.346000      | 66.671300            | 0.778000                        |

Figure 19 The overall view of log processing panel.

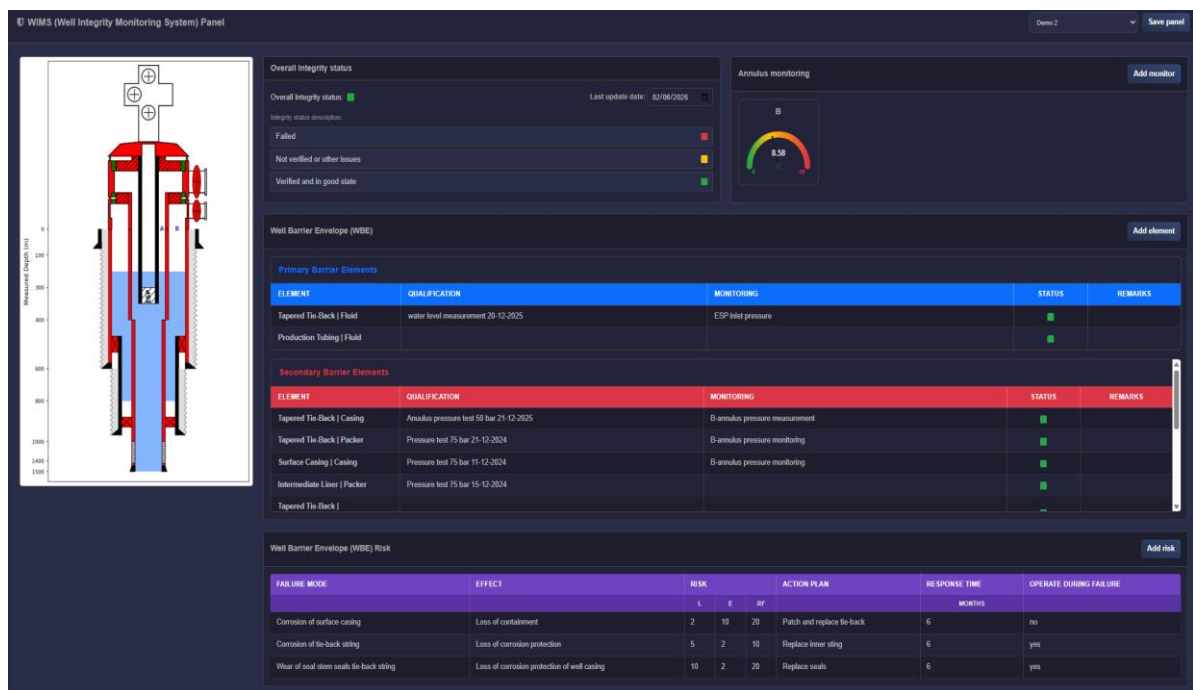


Figure 20 Example of the WIMS panel.

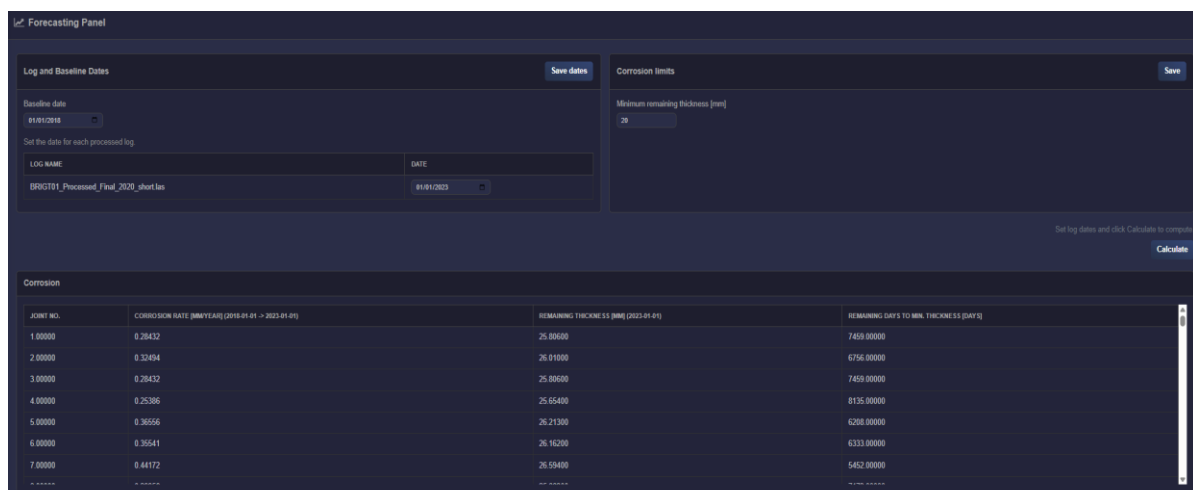


Figure 21 Basic corrosion calculations.

## 7. Subsurface temperature monitoring

Proper management of reservoir temperatures is crucial for the long-term planning and operation of a geothermal energy production system. If temperatures in the injection reservoir drop at a too high pace, it can end up affecting the production reservoir as well, leading to reduced production temperatures, lower heat/energy production (and therefore worse economic margins). In the worst-case scenario, this can end up halting the doublet's energy production capacity in its entirety.

To prevent such situations from occurring, monitoring of reservoir temperatures is key. In many modern geothermal energy production and storage systems, this is done through Distributed Temperature Sensing (DTS). Distributed Temperature Sensing (DTS) is a fiber-optic sensing technology that provides continuous, real-time temperature measurements along the full length of an optical fiber, often several kilometers long (Khankishiyev, Salehi, Hasanov, & Hu, 2024). Unlike traditional point sensors (thermocouples, RTDs), DTS gives a spatially continuous temperature profile. DTS can be seen as a very long temperature sensor, with temperature readings at every point (e.g., every 0.5–1 meter). DTS works on the principle of Raman scattering, which has a temperature-dependent component to it (Khankishiyev, Salehi, Hasanov, & Hu, 2024). By measuring the backscattering of light shone through the fiber-optic DTS cable, it is possible to sense the temperature along its length.

A DTS system has three major components (Khankishiyev, Salehi, Hasanov, & Hu, 2024):

- A **laser source**, which injects high-energy laser pulses into the DTS cable fiber.
- **Optical receivers** and filters that collect the backscattered laser light.
- A **data processing unit** (interrogator) that processes the collected backscattered light and calculates the temperatures based on the temperature-dependent scattering phenomenon, and the distance of each temperature reading based on time-of-flight of the light through the cable.

DTS can work over cable distances up to 50 kilometers with spatial resolutions of measurements every 0.5-2 meters with an accuracy of 0.5-2 degrees Celsius.

Within the Nieuwe Warmte Nu! project GEMINI has been extended with data ingress and visualization capabilities to retrieve, store, and visualize high volumes of historical and real-time DTS data coming from its interrogator. These developments are described in more detail in the next two subsections, with the first focusing on the developed data-scheme that allows data from a DTS-system to be connected to the GEMINI digital twin with various interrogator models, while the second focuses on the Grafana dashboard that was developed for loading and visualizing DTS data.

### DTS data ingress methods

There are a large number of different DTS systems available on the market, each with their own interrogator models and data processing and ingress methods. To be able to use different vendors of DTS interrogators, a workflow has been set up in which message queuing plays an important role. Message queuing makes it possible to connect two or more systems, especially when they run at different speeds, have different reliability needs, or cannot communicate directly in real time. Message queues (like MQTT, RabbitMQ, Kafka, Azure Service Bus, AWS SQS, etc.) provide:

- At-least-once delivery,
- Automatic retries,
- Persistent message storage (prevents data loss).

This is especially useful when:

- The network is unstable,
- Devices are remote (like sensors in the field),
- You cannot afford to lose data.

In many cases, DTS output is written in a proprietary data file format, like vendor-defined XML structures, while others prefer a more standardized way like HDF5 (a modern data-storage format). In addition, designs aimed more specifically at geophysics application are used, such as the SEEDlink protocol and the

miniSEED subset of the SEED standard. In addition, there are also vendors that support native message queuing, as ZMQ and MQTT.

For the data ingress approach developed for the GEMINI digital twin, every vendor format is converted to a message queue according to the MQTT protocol. A described JSON definition ensures uniform delivery. JSON is a programming language-independent data format. There are examples available on how to convert files such as XML, ZMQ, or miniSEED to JSON, which describe how the JSON file can be sent to the MQTT server. The MQTT server can serve multiple interrogators simultaneously and forward to the underlying time series database supported by GEMINI. There is the choice of an InfluxDB or a PostgreSQL database implementation. In this workflow, an extension for time series data in PostgreSQL to handle large amounts of time series data and serve it to the visualization tool (Grafana) is used. This workflow is shown in Figure 22.

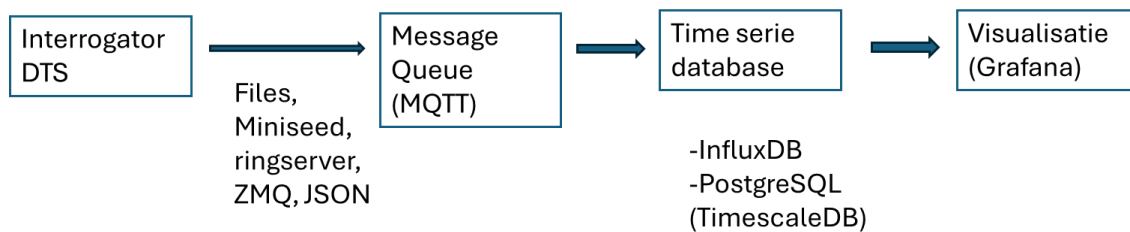


*Figure 22 Schematic representation of how the workflow works, taking data from the interrogator at a message queue, storing it in a time series database, and visualizing it.*

In addition to the data-ingress workflow, a data model (shown in Figure 23) has been designed for PostgreSQL. In the data model, fields and surveys with measurements linked to wells and locations can be recorded. The top level of the data scheme is the “Field”, which describes the area/location where the data has been recorded. Below the field is the “Survey” level. A survey is a specific period of research or monitoring and is specified by a number of wells with fibers/sensors placed inside it. The measurements are stored in relation to the individual fiber/sensor installed at a site. This makes it possible to do advanced querying over all related objects such as wells and sensors.

The necessary SQL and Python scripts have been made available in GEMINI to fill out the required tables so that the DTS data can be recorded and connected to the digital twin. The addition of a time series extension to PostgreSQL<sup>11</sup> makes it possible to quickly search through large amounts of data. Another option is to use InfluxDB as a NoSQL time series database. NoSQL database are very fast in retrieving and providing time-series data but lacks the relational properties of a SQL database such as PostgreSQL.

<sup>11</sup> <https://www.postgresql.org/>

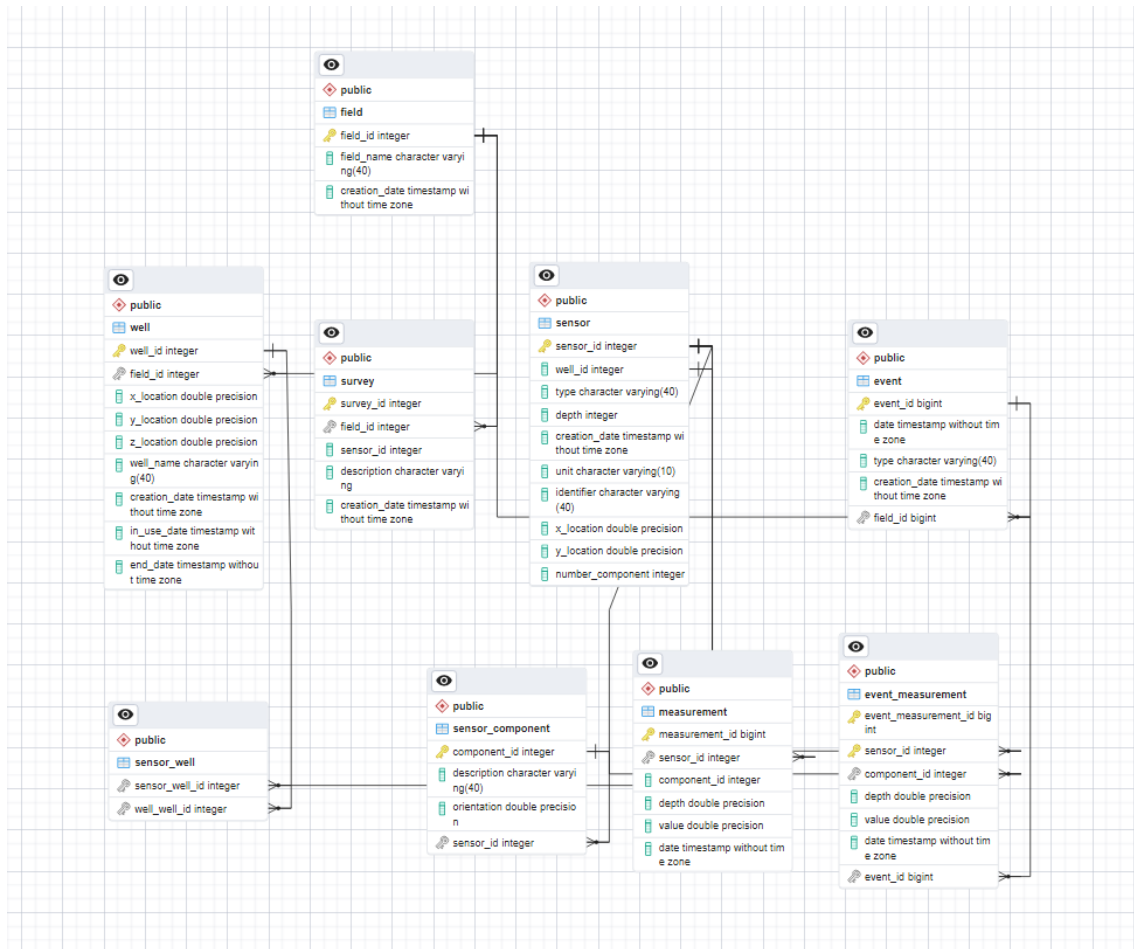


Figure 23 The object-relational database management system RDMS PostgreSQL: with relations between field, survey, wells and measurements shown.

## DTS monitoring dashboard

Once the DTS data is connected from the DTS system to the GEMINI digital twin, it needs to be made available for monitoring by the user. This is done through a Grafana dashboard shown in Figure 24. The dashboard designed to monitor DTS data integrates multiple visualization panels and interactive filters to enable temperature analysis across fields, surveys, identifiers, time ranges, and depth intervals. The solution is built on Grafana, and PostgreSQL is used as the primary data source.



Figure 24 The overall view of the Grafana DTS visualization dashboard.

The individual panels that make up the overall dashboard will be explained in more detail in the next subsection. Each panel relies on predefined variables that control filtering and data selection. However, for clarity, the panels will be described first, followed by an explanation of the variables they use.

## Panels

A panel is a visual element within a dashboard that presents data, typically as a graph, table, map, or another type of visualization. The dashboard contains five panels in total including one heatmap, two XY charts with different functionalities, one table view, and a geomap. These panels display the experiment associated with the selected identifier, after the field, and survey have been chosen in the filtering workflow:

- The **Heatmap** (Figure 25) was generated using the mosaic plugin, a Grafana panel designed for visualizing large datasets as heatmaps. This panel provides several additional features and a much wider range of styling options. In the dashboard, it is used to present temperature data over a one-day period, starting from the selected date and time. Since the dataset is very large, the heatmap shows temperature values at 30-minute intervals using averaged measurements across the depth interval defined by the selected “Start Depth” and “End Depth”. The temperature values are shown on the left axis, while the right side displays a color scale representing temperature variation, and the timestamps are displayed along the bottom axis.
- The **Depth Filtered XY Chart** (the top plot in Figure 26) visualizes two separate series, each generated through a different query in Grafana corresponding to the selected start and end depth. These two queries produce the two lines shown in the chart: the green line represents the start depth, and the yellow line represents the end depth, as indicated in the legend (Figure 26). Similar to the heatmap, it follows the same filtering structure.
- The **Full Cable XY Chart** (bottom plot in Figure 26) displays the temperature measured along the entire cable at a specific day and time. The starting depth and ending depth filters are not applied to this panel, as it displays data across the entire cable.
- The **Table View** (left panel in Figure 27) displays temperatures at 30-minute intervals over a one day period for the selected field, identifier, and depth range, similar to the heatmap and the Depth Filtered XY chart. The rows change color based on the data values and their corresponding ranges.
- The **Geomap** (right panel in Figure 27) displays the location where the selected data was collected. This location information is visualized by retrieving the longitude and latitude values associated with the chosen field and identifier from the dataset.

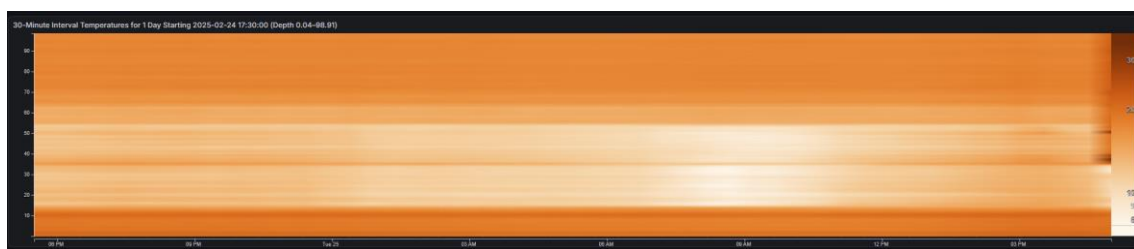


Figure 25 The heatmap panel of the Grafana DTS visualization dashboard.



Figure 26 The depth-filtered and full cable data plot panels of the Grafana DTS visualization dashboard.

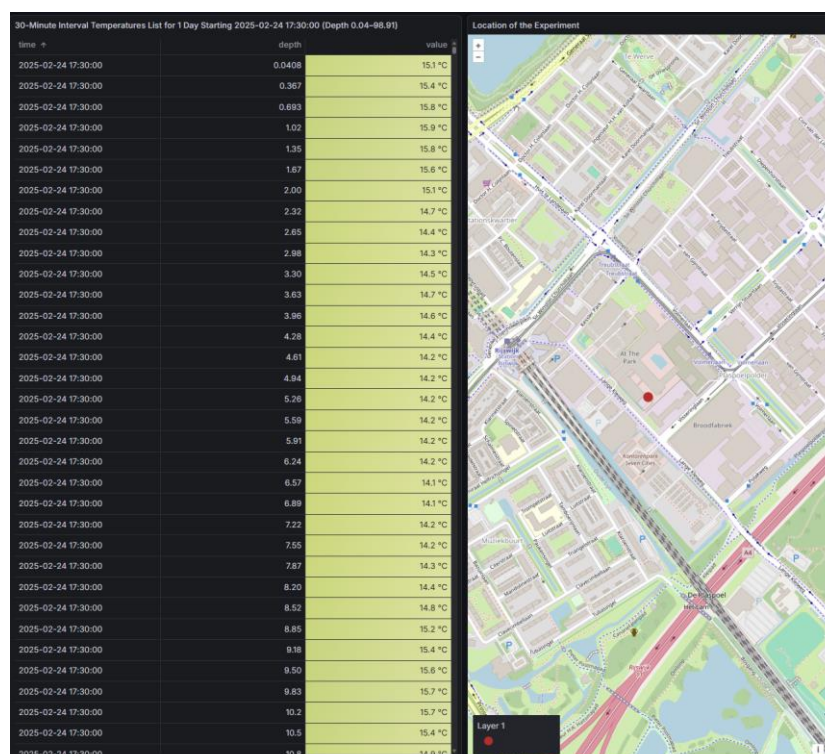


Figure 27 The table view and geomap panels of the Grafana DTS visualization dashboard.

## Variables

In Grafana, a variable is a dynamic value used for filtering data when creating panels or charts. A variable becomes dynamic by allowing the user to select its value from the filtering menu. During panel creation, these variables are inserted into the queries, and their selected values control how the data is filtered. For example, the “Field” variable represents the experiment location, and by selecting a location from the filter menu, the variable’s value is applied to the underlying queries. Furthermore, all these variables are interconnected, and when filtering starts from the field variable, the dataset is narrowed down, and the remaining variables load only relevant options. The filters change depending on which experiment the user wants to view and in which field:

- The **Field** represents the location where the experiment was conducted. Once a field is selected, the user can choose which survey from that field can be viewed.
- The second filter in the workflow is the **Survey**. A survey represents a specific measurement session carried out within the selected field. Each survey contains one or more identifiers that correspond to the individual measurement sensors used during that session. After selecting a field and choosing a

Survey, the user can view the available identifier options associated with that survey through the Identifier filter.

- The **Identifier** represents the individual sensor or measurement line within a survey, and selecting it specifies the exact dataset to be displayed. Once an Identifier is selected, the user has access to more detailed filtering options to perform analysis on the experiment data associated with that experiment. In other words, at this stage, the user gains access to the measurements collected by the selected identifier.

To further refine the filtering process, after selecting a specific identifier, the user can additionally select a **date** and a specific **time of the day** to view temperature variations for the chosen time interval. The day and time values, which were originally stored together in the dataset, were separated using a query during variable creation. Due to the high volume of data, the time range displayed in the charts is limited to 30 minutes by taking average and for 1 day. In the dashboard, data is shown for a one-day period starting from the selected date and time. Because the dataset is very large, the temperature values within this 24-hour or 1 day period are aggregated into 30-minute intervals by calculating the average for each interval. These predefined intervals help ensure clarity and performance when visualizing the data. This time range limitation does not apply to the Full Cable XY Chart in which the entire cable is displayed.

Apart from these variables, additional parameters have been defined for two filtering options, **start depth** and **end depth**, to enable viewing a specific depth range. As outlined above, this does not apply to the graph that displays the entire cable. Which panels are affected by these variables or filters has been explained in the Panels section.

## 8. Summary

This report presented the modelling framework and implementation of the GEMINI geothermal digital twin, describing both the integration of previously developed models and the development of new physics-based and data-driven components. For each model, the governing equations, required inputs, generated outputs, assumptions, and known limitations were documented. Where available, validation procedures and benchmarking results were discussed to clarify model performance and applicability boundaries.

The implemented models cover key subsystems of geothermal production, including reservoir inflow behavior, wellbore hydraulics, production performance, well integrity risks such as corrosion risk estimation, and distributed temperature sensing (DTS) data processing. For each model, the report specified:

- The mathematical formulation (e.g., IPR relations, PVT correlations, pressure-loss equations),
- Required operational and design inputs (pressures, temperatures, flow rates, salinity, geometry, etc.),
- Calculated parameters (e.g., flow rate, bottom-hole pressure, corrosion indicators),
- Assumptions and simplifications (steady-state operation, single-well representation, linear inflow, etc.),
- Model limitations and validation status.

All models were integrated into the GEMINI digital twin framework and operationalized through modular, real-time calculation engines. The implementation enables continuous computation of system states based on live data streams. The framework includes visualization dashboards and interactive offline applications, allowing users to perform scenario analyses, parameter sensitivity studies, and engineering assessments outside of real-time operation. This ensures both operational monitoring and engineering decision support functionalities are embedded within a single coherent platform.

The added value of the implemented models lies in their ability to support geothermal operations and asset management in a structured and transparent manner. The GEMINI digital twin enables:

- **Production monitoring:** Improved understanding of plant and well performance, productivity monitoring, a real-time ESP monitoring and early identification of deviations from the expected behavior, quantification of operational margins and risks, and support for production optimization and maintenance planning.
- **WIMS:** an integrated approach to combine different data sources and models to monitor well integrity risks, corrosion rate calculations based on the historical data and logs, and a comprehensive method to identify well barrier envelopes which is supporting the risk managements with respect to wells.
- **Subsurface monitoring:** provides a standardized approach to ingest DTS data and visualizing it, more informed insights on the temperature profiles which can be very crucial for the subsurface thermal energy storage systems.

The final deliverable of this project is an open-source release of the GEMINI geothermal digital twin and the associated model libraries. The models described in this report are designed to be modular, extensible, and accessible to the wider geothermal community. The open-source approach encourages transparency, peer review, community-driven validation, and collaborative improvements across operators, researchers, and technology providers.

At the same time, several limitations of the current implementation are provided:

- Apart from density and viscosity, the current brine PVT model returns a constant values for all other fluid properties and does not yet account for full compositional variability.
- Heat loss equations assume a constant heat transfer coefficient.
- The IPR model assumes linear inflow behavior and represents a single-well system.
- Most models operate under steady-state assumptions and do not capture transient dynamics.
- DTS data ingestion cannot be fully universal and may require customization depending on site-specific

sensor configurations and data structures.

- Certain degradation and failure mechanisms are represented in simplified form.

These limitations do not undermine the framework but rather define its current maturity level and guide the next development steps. Looking forward, several developments are already in the pipeline. These include expansion of monitoring capabilities to additional components such as heat exchangers and filtration systems to give an overview of the full systems performance indicators. In addition, development of equipment failure forecasting models (e.g. ESP monitoring and degradation prediction) can enhance the predictive capabilities of the digital twin. Some of the current models such as corrosion rate need to be refined and validated and extended with other corrosion mechanisms. Regarding the WIMS, introduction of indirect model-based corrosion calculations, annulus pressure modelling and implementation of basic erosion models is foreseen as the next steps. Finally, further field testing and benchmarking of the implemented models are required.

The open-source codebase will remain under continuous development, with iterative updates driven by field feedback, validation results, and community contributions. This ensures that the digital twin evolves alongside operational needs and technological advances.

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