

GEMINI: An Open-Source Digital Twin for Geothermal Energy

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TNO

WEP work well together

Helin

GAIA ENERGY

hvc energie en hergebruik

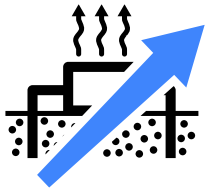
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Development and Demonstration Projects

- A national growth fund project in the Netherlands to demonstrate digital twin in geothermal systems and Aquifer thermal energy storage (ATES)
  - 3 sites, Live demonstrations
  - Monitoring the implementation for > 6 months
  - Full value chain onboard
  - Open-source libraries released in 2026

Motivation

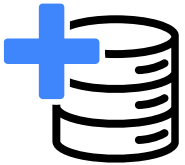
Growth of the geothermal sector

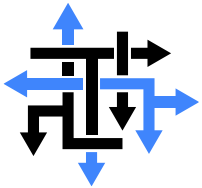




Source: https://vb.nl/nl/geothermie

Increase in data availability





Complex production and operation



Knowledge transfer from other industries

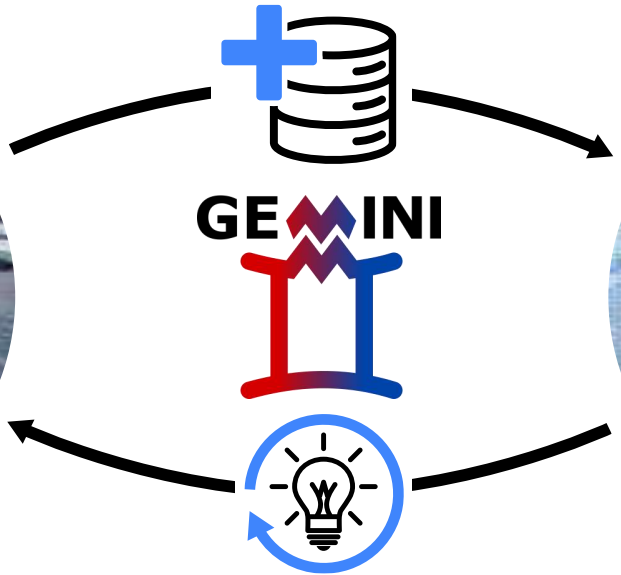
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The Digital Twin

Physical system



Source: https://vb.nl/nl/geothermie



Digital system

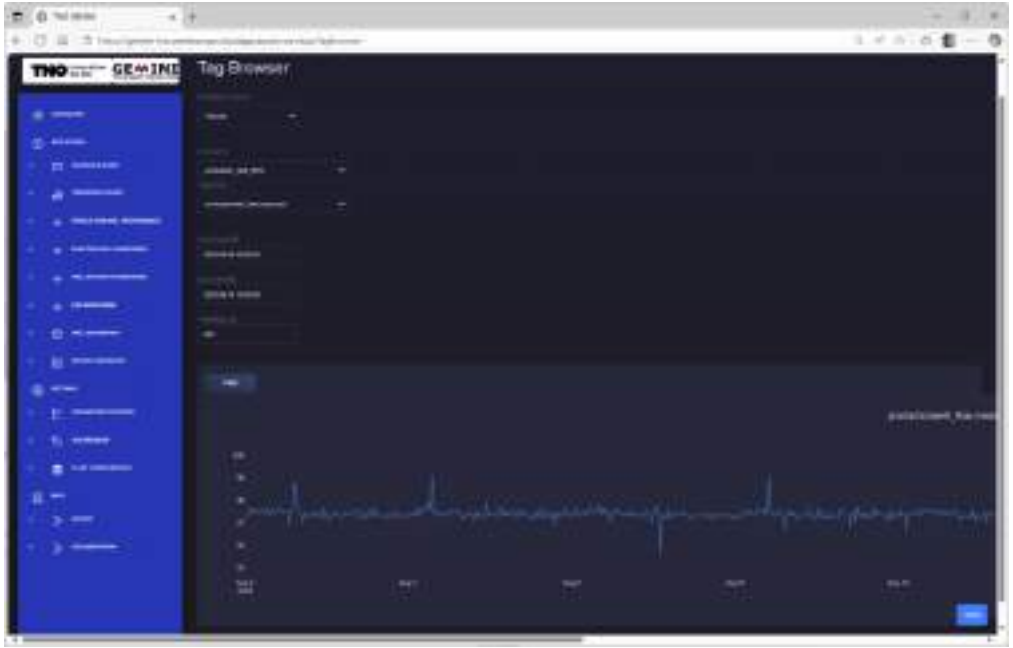


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The Geothermal Digital Twin

Central location for data access





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The Geothermal Digital Twin



Real-time monitoring



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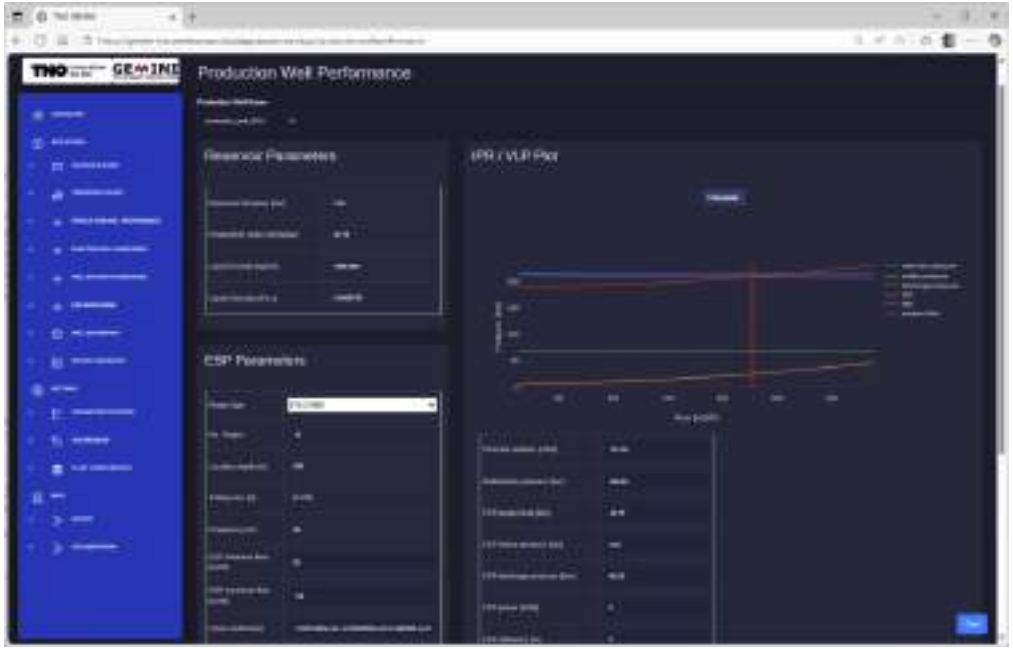
The Geothermal Digital Twin

Central location for data access



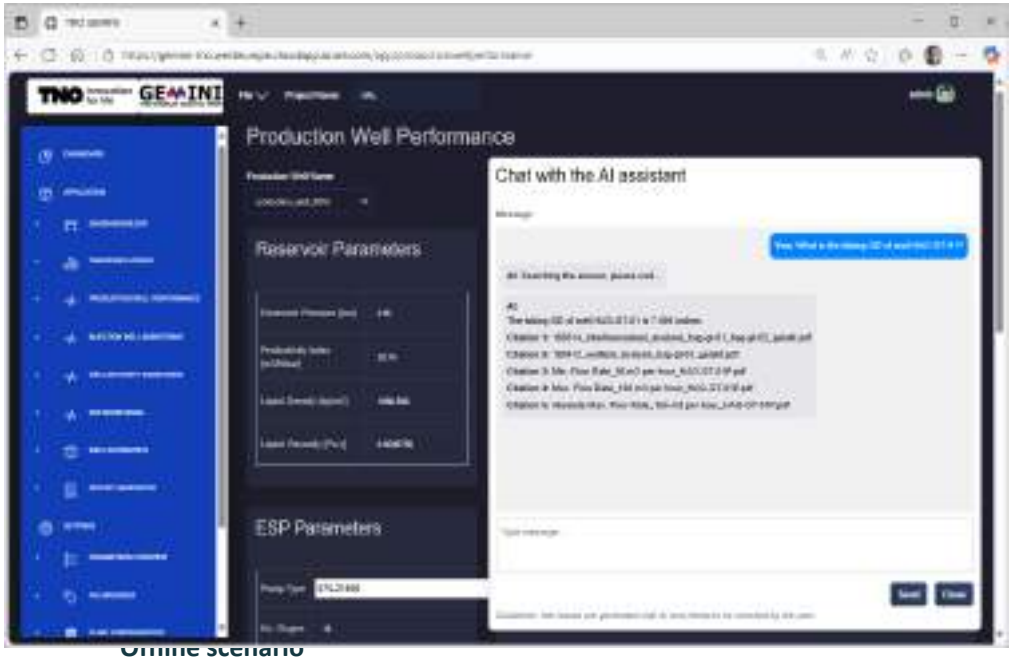


Offline scenario analysis



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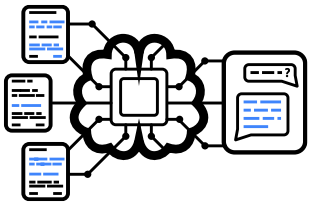
The Geothermal Digital Twin



Offline scenario analysis

Real-time monitoring





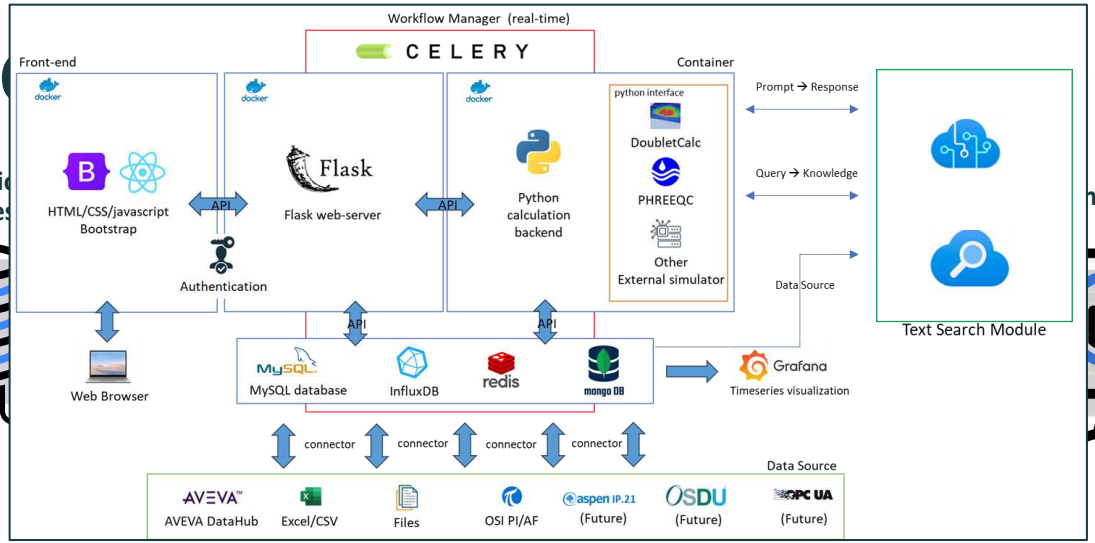
AI & chatbot functionalities

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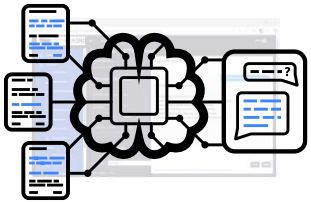




Offline scenario analysis



Open source development



AI & chatbot functionalities

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The Geothermal Digital Twin

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GEMINI

Real-time monitoring

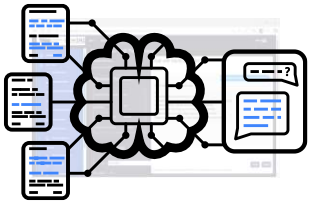




Offline scenario analysis



Open source development

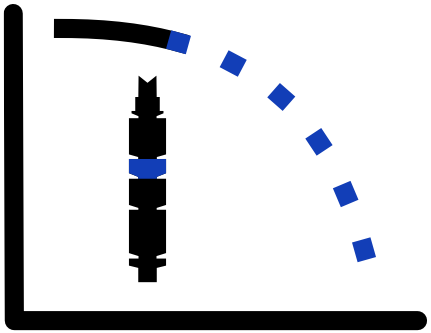


AI & chatbot functionalities

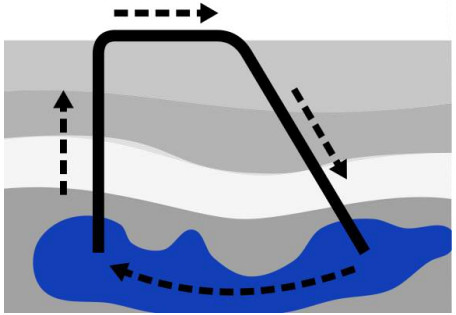
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From Platform to Operational Applications

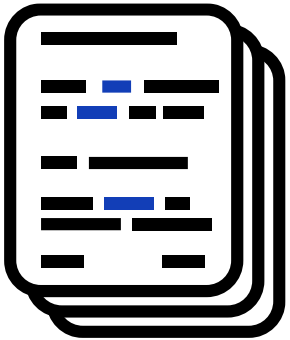
Predictive maintenance



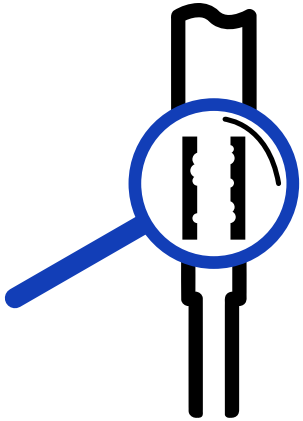
Subsurface monitoring



Generative and Agentic AI



Well integrity management

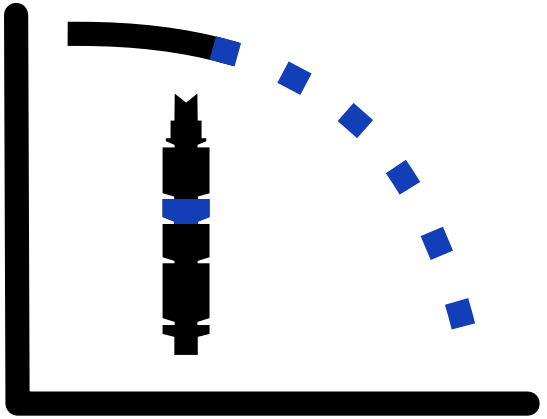


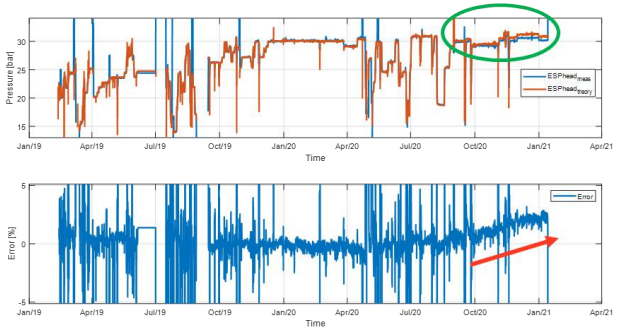
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Predictive Maintenance

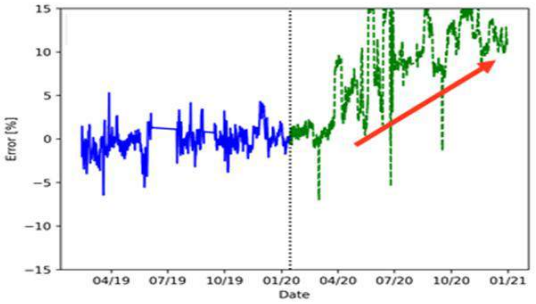
ESP and Injection Pump Monitoring

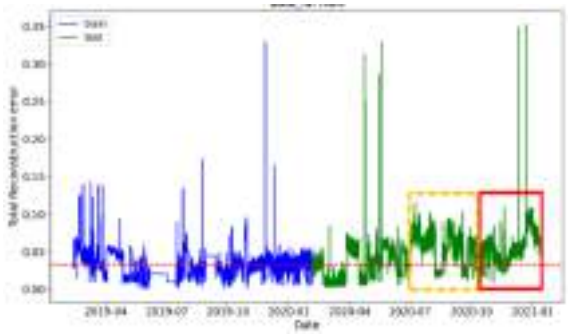
- Development of (data-driven) monitoring and predictive maintenance models
- Monitoring of Electrical submersible pumps (ESP) and injection pumps





ESP vibration



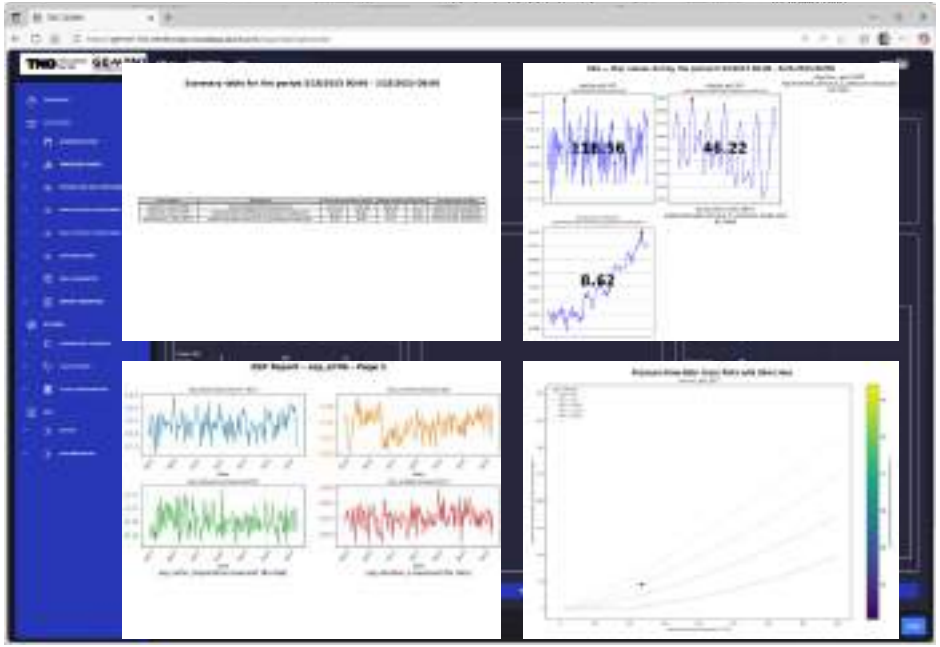


Early signs of degradation visible 6 months prior to the failure.

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AI chatbot

- Retrieval-Augmented Generation approach
  - Allows for asking questions about information in reports/documents
- Fully open-source GEMINI integration using:
  - Langchain framework (Python)
  - ChromaDB database for storing embeddings
  - Ollama to interface with open-source LLM’s
- Automatic report generation

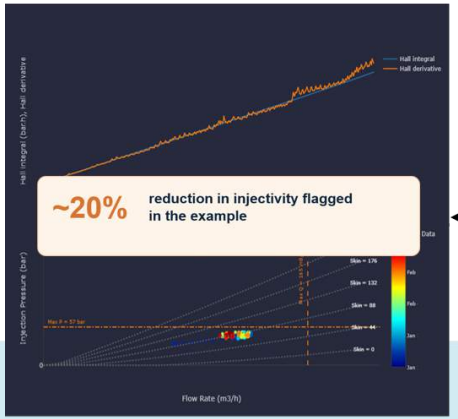


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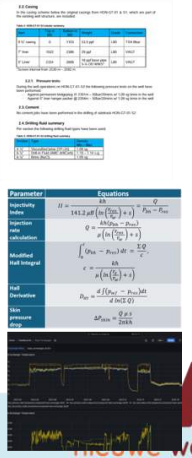
Agentic AI

- From answering questions to executing multi-step workflows
- AI Agents autonomously combine data, models, tools, and domain knowledge
- Human experts remain in control through validation and governance

Prompt: estimate the injectivity change in the first 3 months of this year of injection well XYZ (From January to March) using Hall integral and Hall derivative plots. Make sure you calculate the skin coefficient for this period.







Why Open-Source?

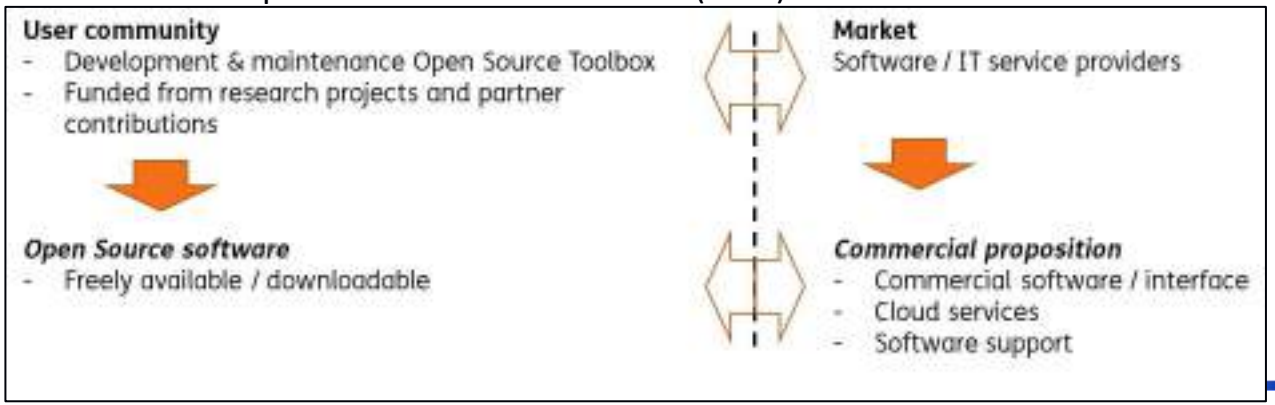


Open-source community to support the digital twin's ecosystem

- Management and maintenance open-source codes
- Further developments based on user feedback and market demand
- Technical documentation and user sessions

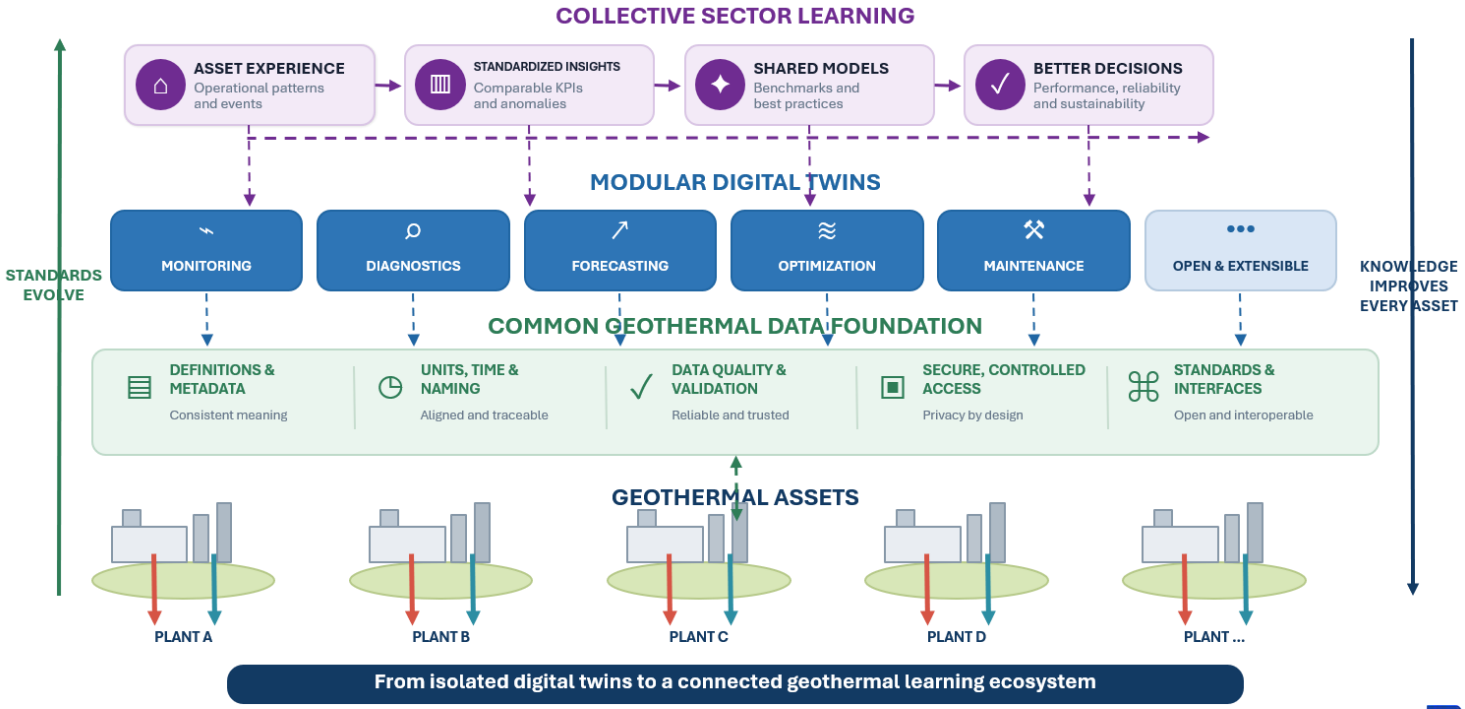
Commercial Software / IT providers:

- Deploy the digital twin in the market and provide training and support to users
- Develop and offer software service (SaaS)



Connecting Data Standards and Digital Twins

- A Shared Digital Foundation for the Geothermal Sector
- Common data standards make assets interoperable. Digital twins turn standardized data into decisions. Collective learning turns those decisions into sector-wide progress.



Summary

- Connect fragmented plant data, models and operational knowledge
- Detect problems earlier and support better operational decisions
- Reuse open modules instead of rebuilding solutions for every asset
- Scale from individual digital twins to collective sector learning, you can already be part of the community!

The innovation is not only a digital copy of the plant. It is a learning operational system that improves with every asset and every use case.



https://github.com/GEMINI-Digital-Twin

Thank you!

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WEP work well together

Helin

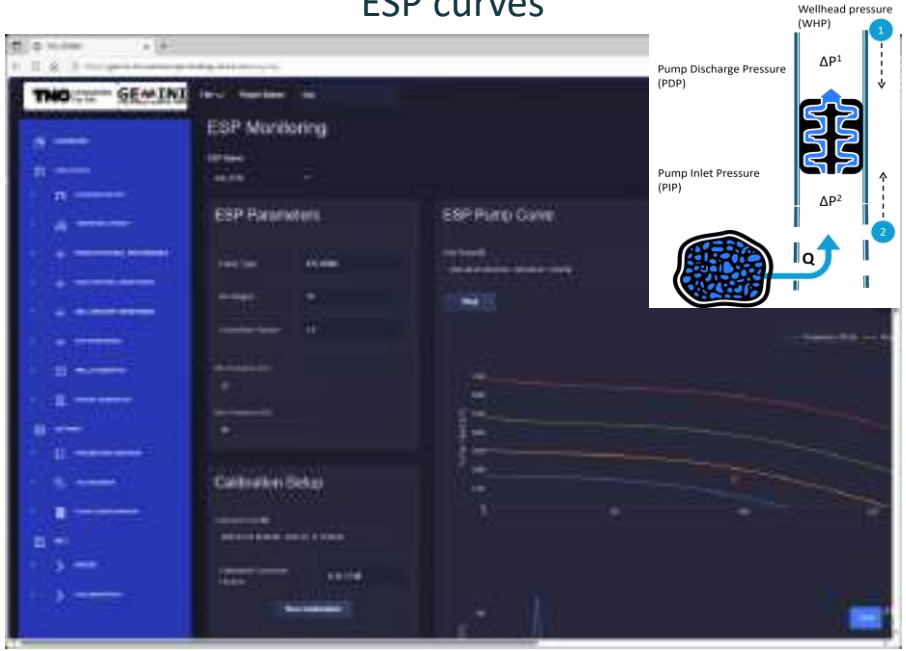
Aardyn Geothermie ontwikkeling & beheer

hvc energie en hergebruik

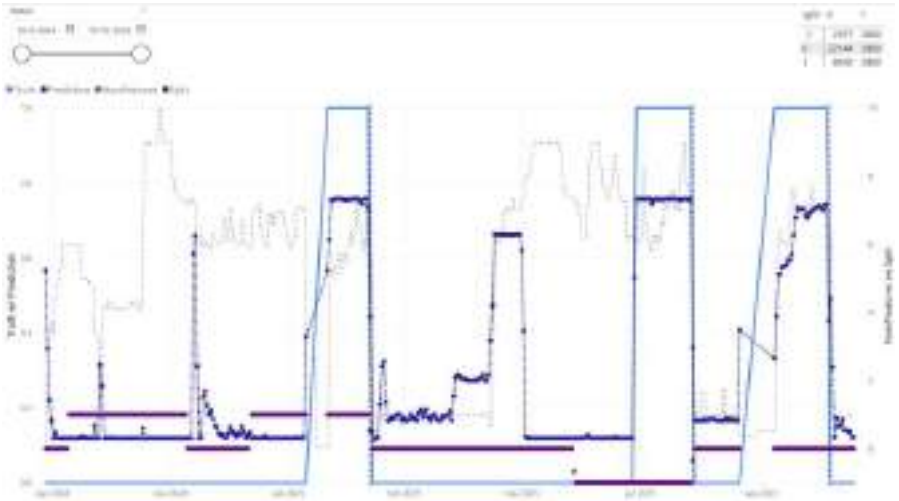
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ESP Monitoring and Prediction

Monitoring ESP Performance, Auto-calibration of ESP curves



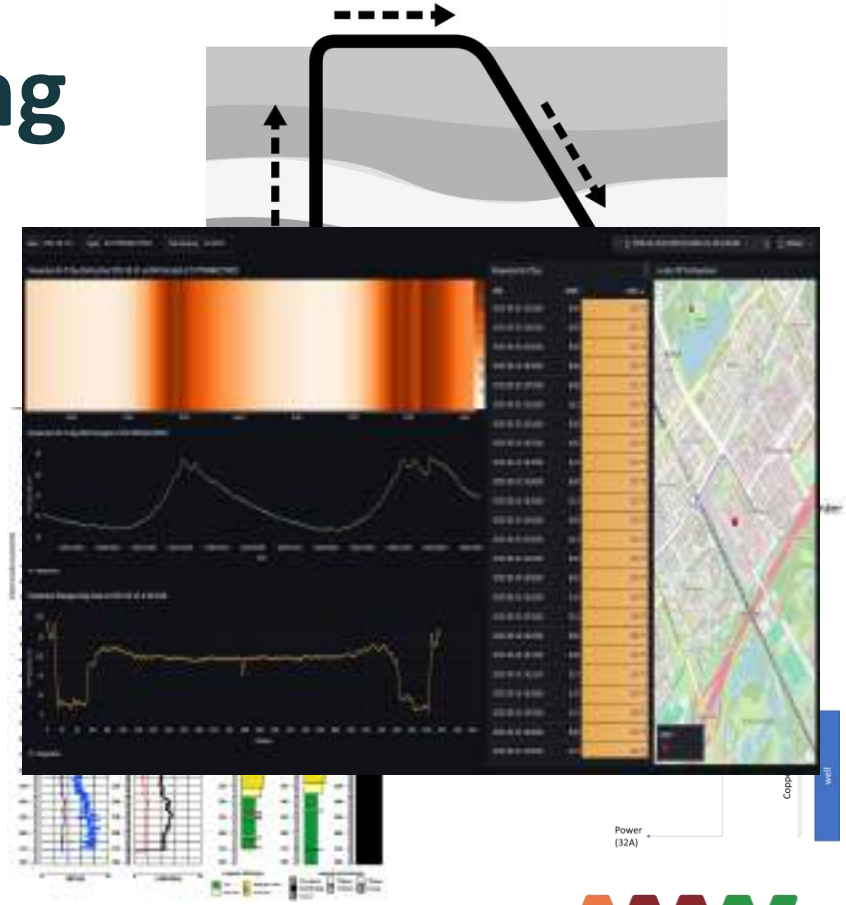
Forecasting ESP failure in 30 days



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Subsurface Monitoring

- Focus on reservoir temperature monitoring (DTS)
- Application: Aquifer thermal energy storage systems (ATES)
- Monitoring and anomaly detection of reservoir temperature
- A well with fibre optic cable already installed. The fibre optic cable was attached to the casing by tape and tie wraps.
- Both active and passive DTS measurements.



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Pilot Sites

- Three sites:
  - Trias Westland
  - Haagse Aardwarmte Leyweg (HAL)
  - Heat storage pilot well at RCSG



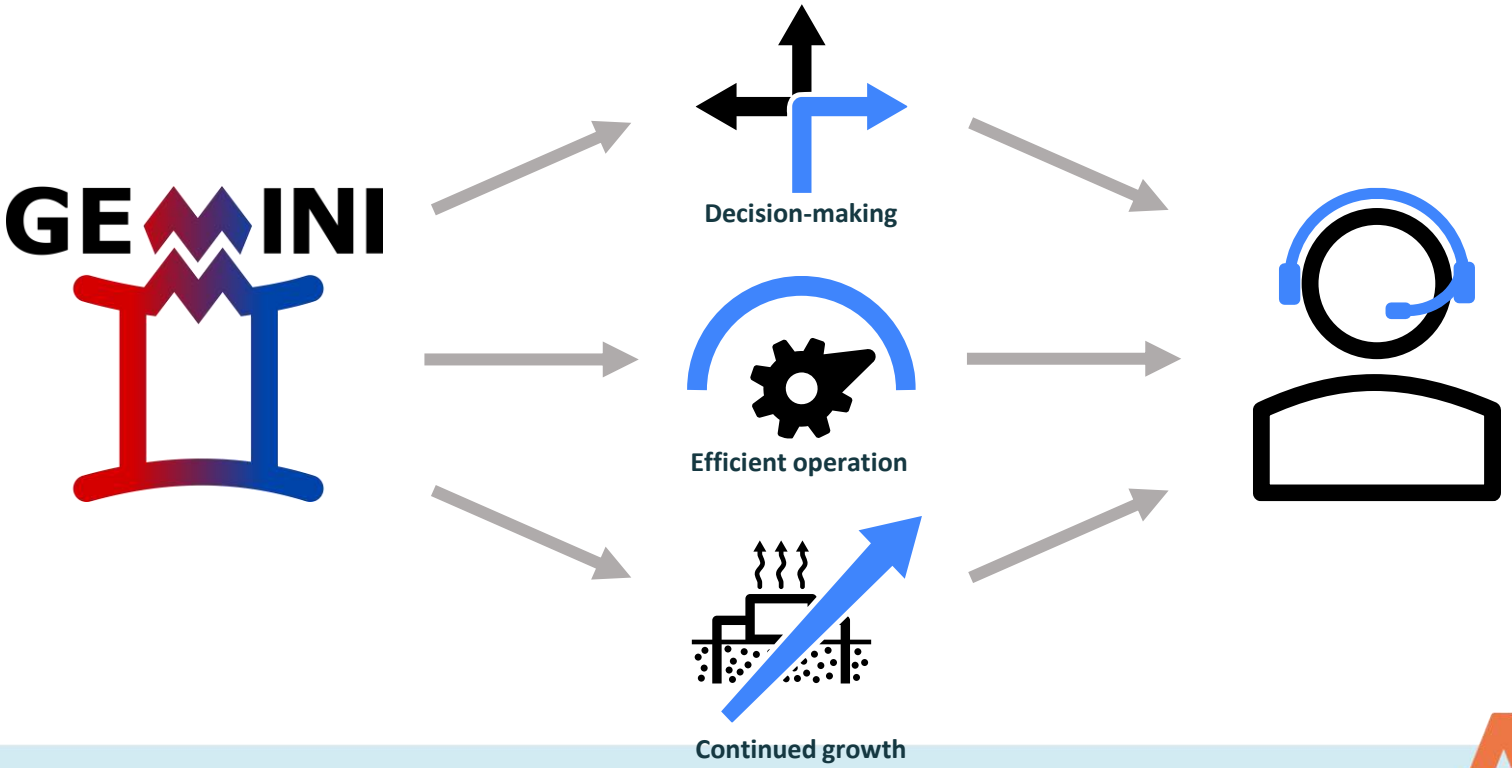






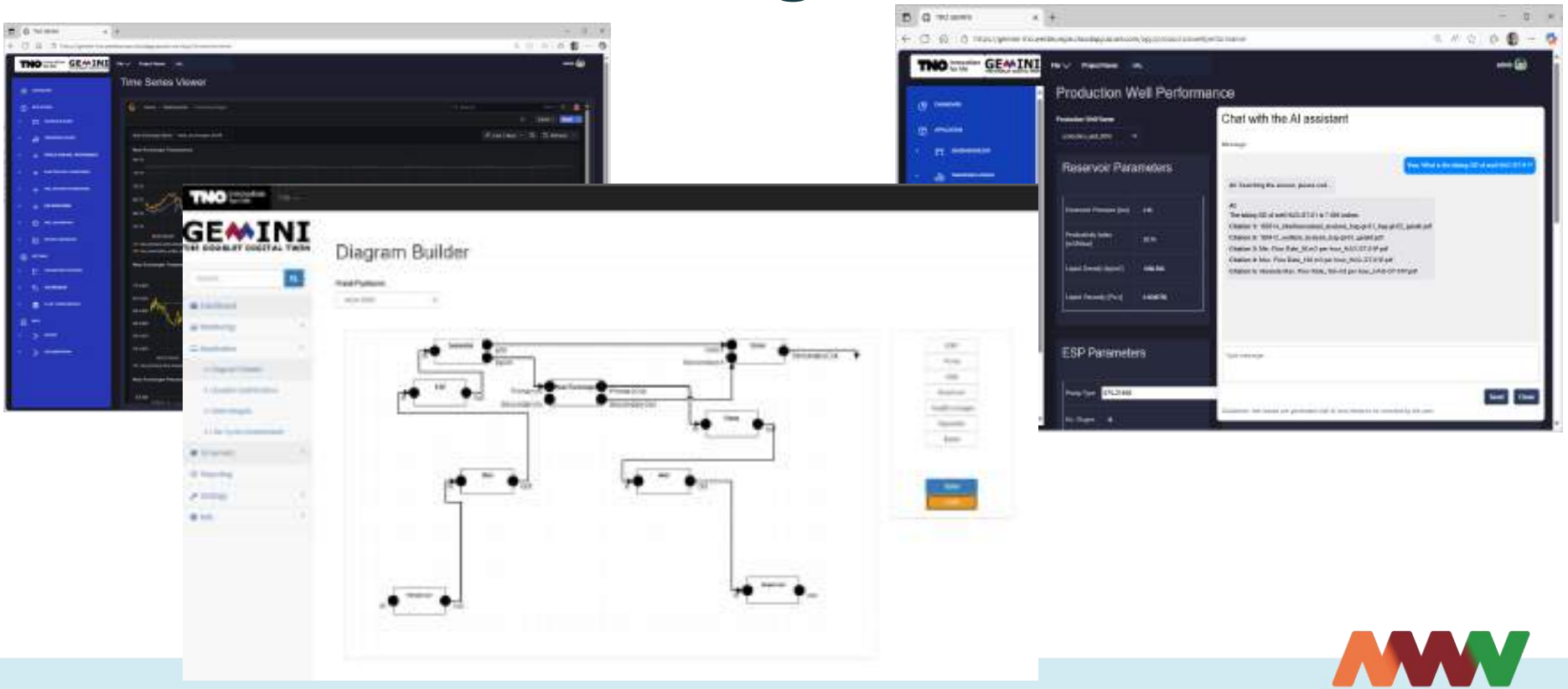
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Supporting operators



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The Geothermal Digital Twin

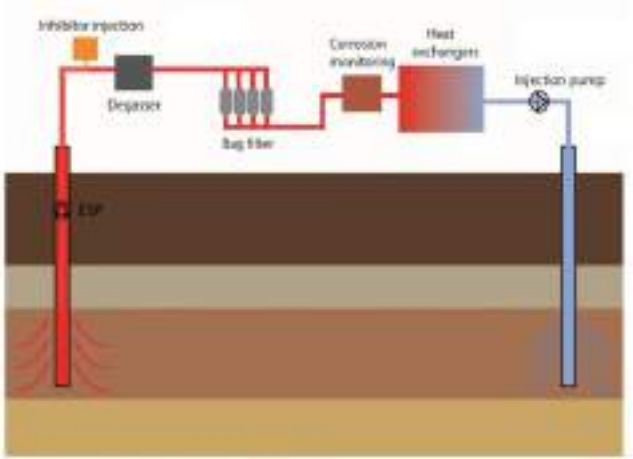


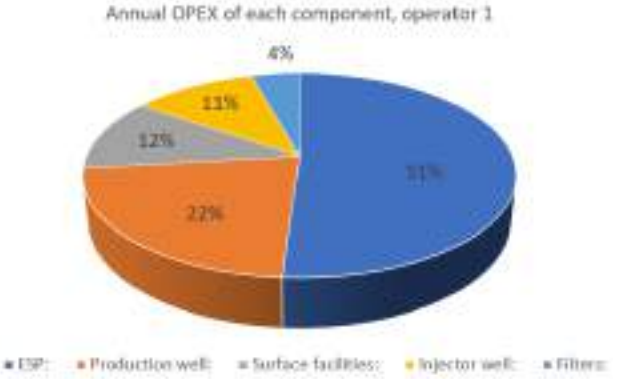
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The current geothermal ESPs have several shortcomings;

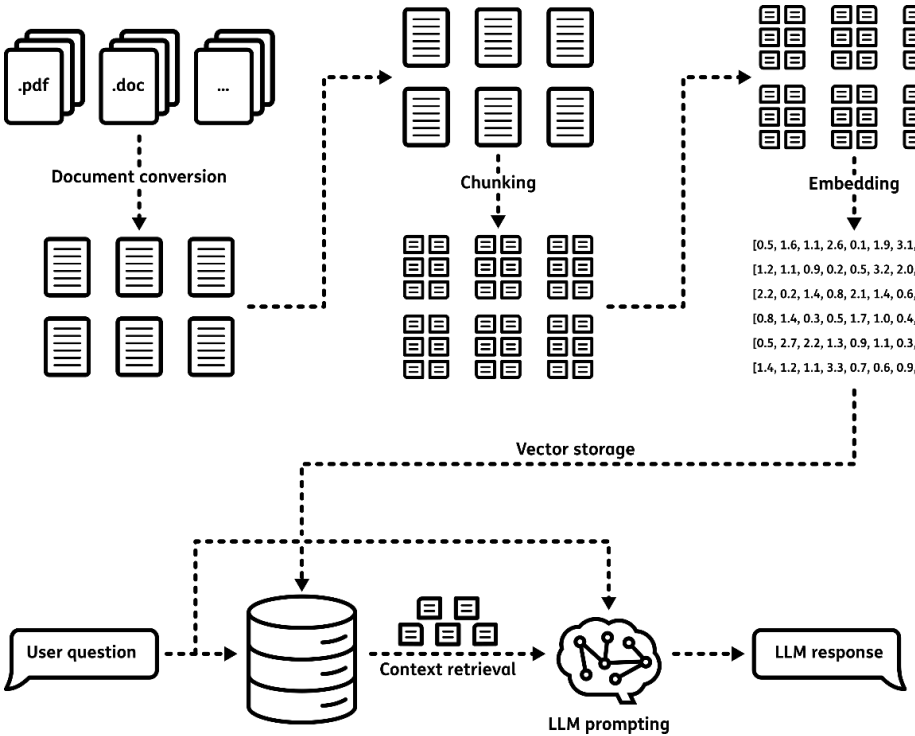
- Monitoring and maintenance planning of critical components, e.g. heat exchangers, ESP, …
- Some components have relatively **short lifetime** leading to **frequent failures**
- operational envelope should accommodate with production variations (P, rates, clogging,…)
- Lack of **proactive monitoring** of system performance during the operation
- High **costs** associated with **inspection** and **replacement**

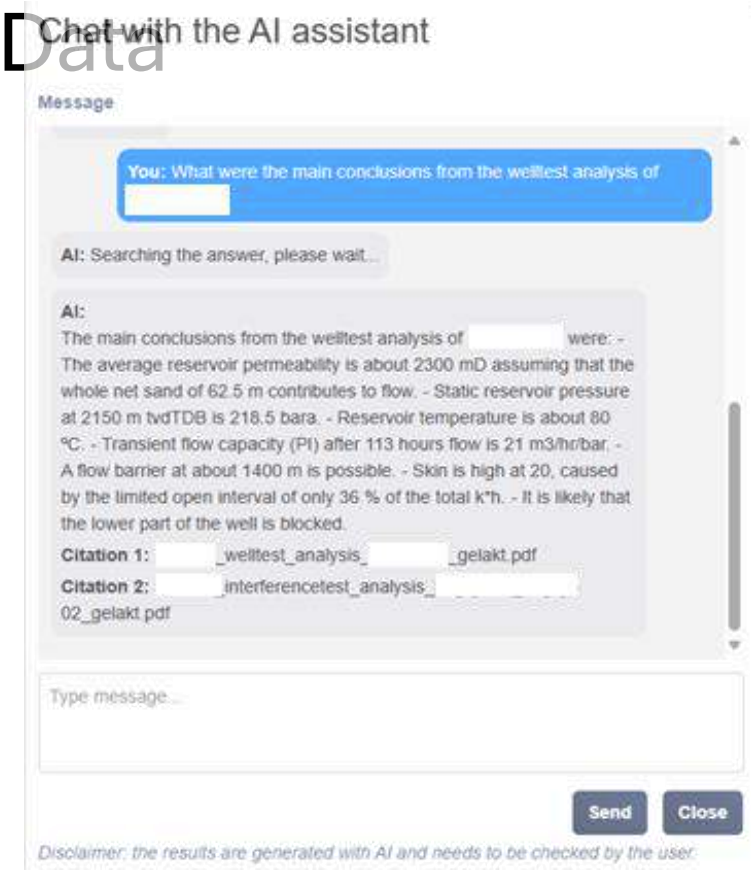
Suboptimum operation of the ESP caused by lack of proper monitoring and operator errors



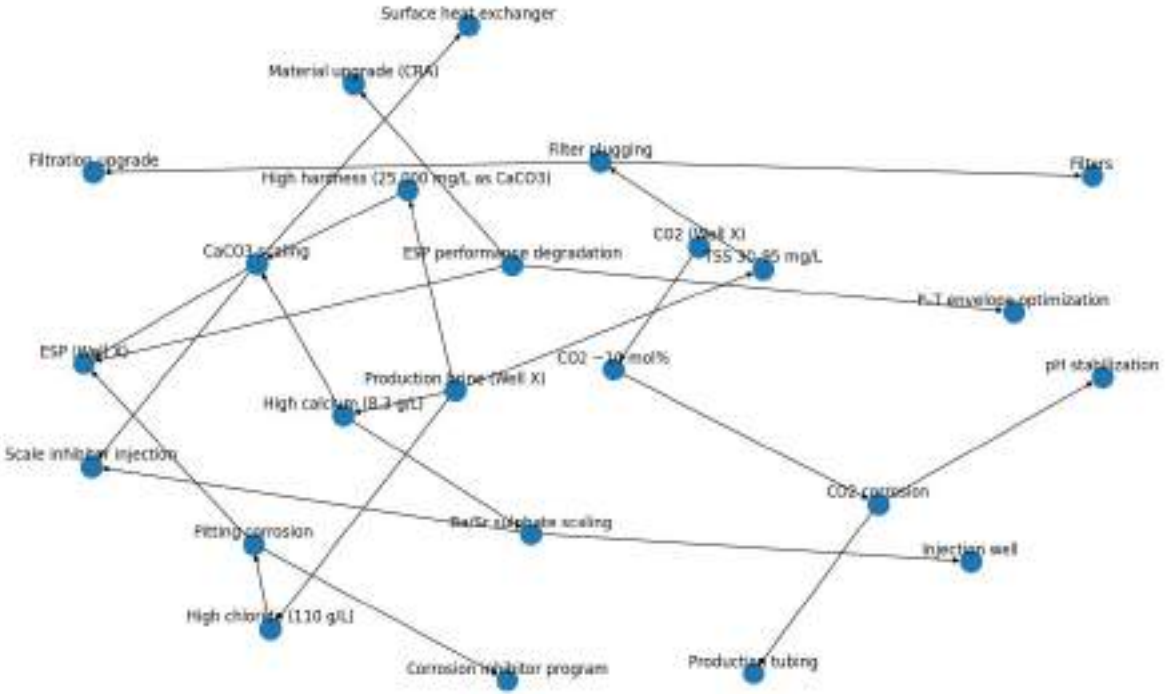


Example: Text Data



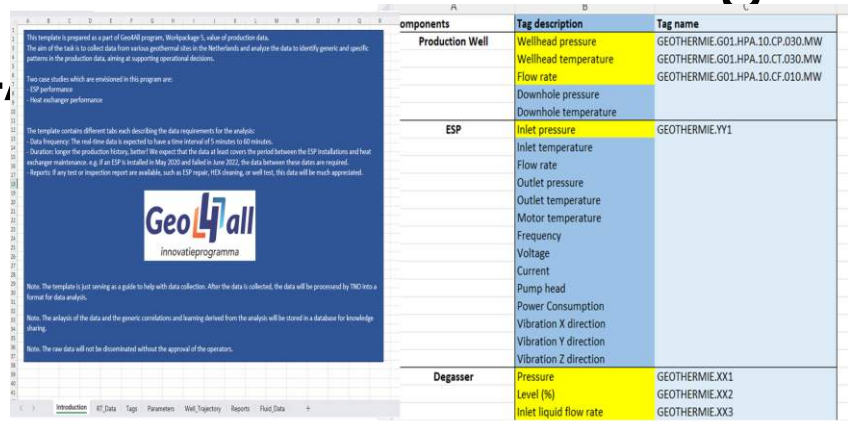


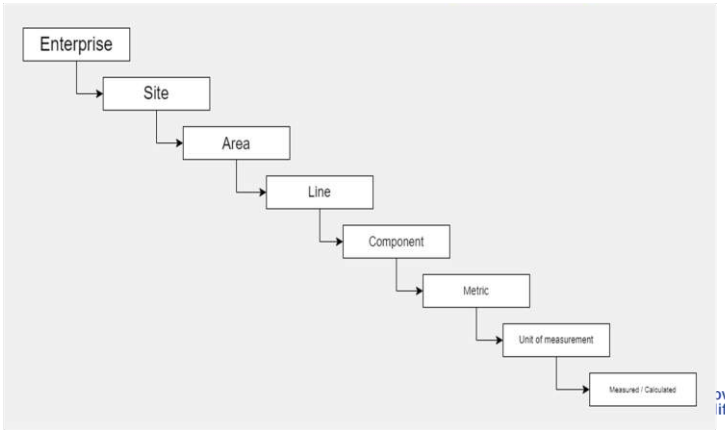
- Combine with knowledge graphs gives both language understanding and structured reasoning (context-aware operational decisions).
- Use LLMs and RAG to extract entities and facts from reports/logs, then store rules, relations, and causal links in a knowledge graph.
- Graph-grounded LLM reasoning produces traceable, actionable operational insights and recommendations.



From Individual Assets to Collective Learning: Geo4All

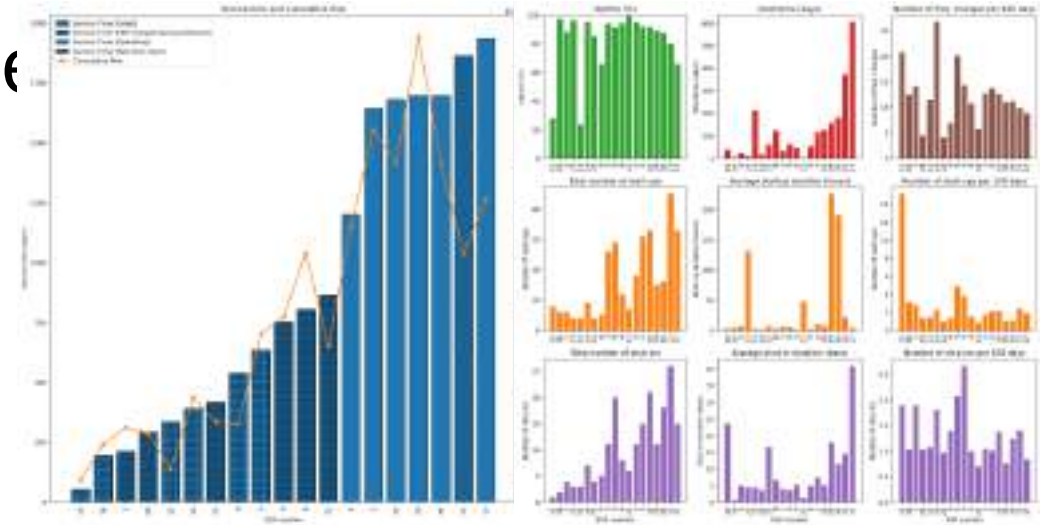
- WP5: Focuses on collective learnings from deep geothermal projects (scope: time-series data, operation and maintenance)
- Standardized template to define critical components and their key characteristics
- Data collected from 18 sites (more in progress)
- KPIs have been defined: performance, reliability, and sustainability indicators
- Three case studies are selected:
  - ESP and pump performance monitoring
  - Naturally Occurring Radioactive materials (NORM)

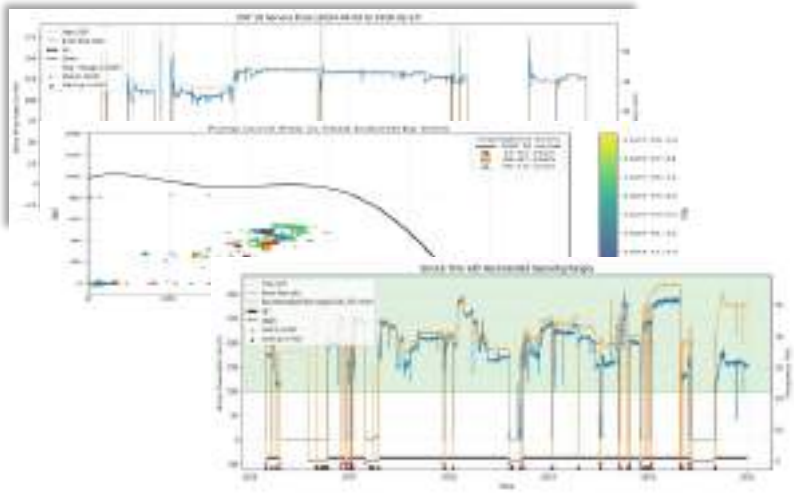


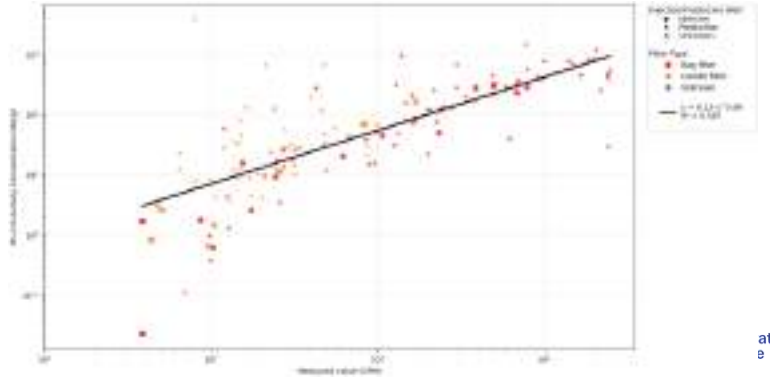


Ge

	Well 1	Well 2	Well 3	Well 4	Well 5	Well 6	Well 7	Well 8	Well 9	Well 10	Well 11	Well 12	Well 13	Well 13	Well 14	Well 15
Brine flow rate	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes		Yes	Yes	Yes	Yes	Yes	Yes	Yes
wellhead pressure	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
wellhead temperature	Yes		Yes	Yes	Yes	Yes	Yes		Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
intake pressure ESP	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes			Yes	Yes	Yes	Yes	Yes
intake temp. ESP	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes			Yes	Yes	Yes	Yes	Yes
discharge pressure ESP							Yes								Yes	Yes
discharge temp. ESP										Yes	Yes					
ESP Motor temperature	Yes	Yes	Yes	Yes	Yes	Yes		Yes	Yes	Yes	Yes	Yes	Yes	Yes		
Vibration (Vx)		Yes		Yes	Yes			Yes	Yes	Yes	Yes					
Vibration (Vy, Vz)	Yes	Yes	Yes	Yes	Yes	Yes		Yes	Yes	Yes	Yes	Yes	Yes	Yes		
ESP voltage	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Freq. ESP	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
ESP Elec. Current	Yes		Yes		Yes	Yes	Yes	Yes		Yes	Yes	Yes	Yes	Yes	Yes	Yes
Temp. Upstream Heat exchanger							Yes			Yes	Yes				Yes	Yes
Temp. Downstreram HEX							Yes			Yes	Yes				Yes	Yes
Pressure upstream HEX							Yes			Yes	Yes				Yes	Yes
Pressure downstream HEX							Yes			Yes	Yes				Yes	Yes



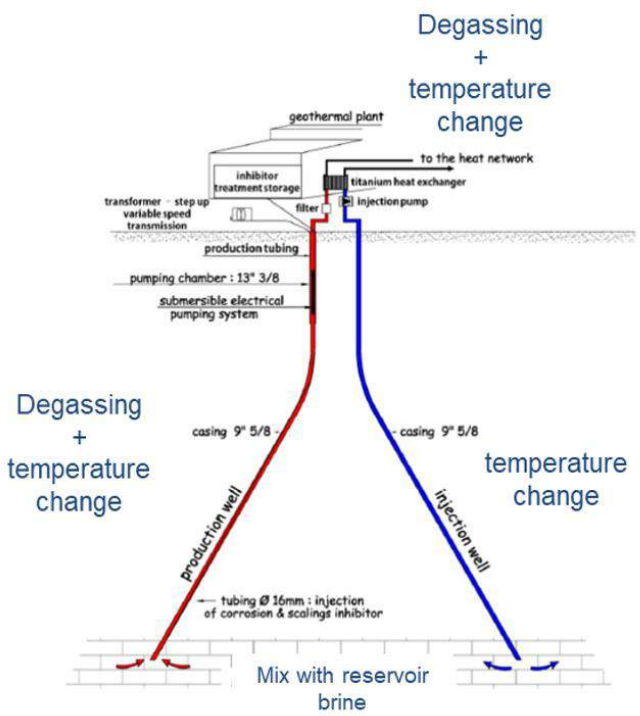




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Motivation

- Growth in geothermal assets in Netherlands and worldwide
- Increasingly complex production and operation
  - Responding to heat demand with a minimum environmental footprint
  - Complex operational challenges
  - Planned and unplanned maintenance
  - Learning curve for operators needs to be accelerated
- Need for a centralized, fast, optimum and robust operational decisions employing data in the life cycle of a plant



From Kervevan et al., 2014

