

CHAPTER 5 – CONCLUSIONS AND RECCOMENDATIONS

5.1. Conclusions

This research aimed to evaluate the role of digitalisation and machine learning in achieving operational excellence and meeting production objectives within a geothermal power plant. Based on the findings from the multi-phase development and implementation of the GOOREMALE system between 2022 and 2025, the following conclusions are drawn:

1. **The advancement of digitalisation in operational decision-making led to a significant reduction in decision-making cycle time.**

The findings confirm that the implementation of digital tools under the GOOREMALE framework—particularly real-time data streaming, centralized dashboards, and structured data processing—led to a substantial reduction in decision-making cycle time. Operational response time was reduced by over 50%, and root cause failure analysis (RCFA) became significantly faster. With this system in place, the reporting cycle time decreased by approximately 44%, from 630 minutes to 355 minutes. Moreover, this transformation enabled higher data accuracy, seamless information flow, and foundational support for advanced analytics, such as anomaly detection and performance forecasting. Through these changes, operational visibility improved across both headquarters and field teams, ensuring quicker alignment and action based on real-time insights. As a result, field-level anomalies were identified and addressed more proactively, translating to more agile and informed decisions.

2. **The optimisation of geothermal operations through machine learning has contributed to enhanced reliability and efficiency, enabling the company to meet production objectives while reducing operational costs.**

Machine learning models successfully learned equipment behaviour from historical datasets, allowing for early anomaly detection and proactive

maintenance planning. Predictive insights—such as those related to vibration anomalies or pressure imbalances—helped prevent unplanned outages and extended equipment life. What-if simulation models supported operational optimization by identifying inefficiencies and quantifying the impact of different strategies. By 2024, production had increased by 4.1% from the previous year and exceeded the annual target for the first time in four years, demonstrating the positive impact of GOOREMALE on overall operational performance.

The implementation of GOOREMALE has contributed to noticeable improvements in the **availability factor** of geothermal assets, particularly in Asset 2 as seen in figure 5.1. Between 2022 and 2023, the availability factor increased from **86.00% to 95.00%**, reflecting the positive impact of digitalization, real-time monitoring, and early anomaly detection introduced through GOOREMALE Level 2. This higher availability was maintained into 2024, indicating sustained operational reliability and reduced unplanned downtime. The reduction in **Forced Outage Factor (FOF)** over the course of the GOOREMALE implementation reflects a significant improvement in operational reliability, particularly for Asset 2. In 2022, prior to the full deployment of GOOREMALE, Asset 2 recorded a high forced outage factor of **10.25%**. Following the implementation of real-time monitoring, condition-based alert systems, and predictive maintenance tools in 2023, the FOF dropped sharply to **3.00%**, and continued to improve to **1.47%** in 2024. This substantial decline highlights the effectiveness of anomaly detection and early intervention strategies introduced by the platform.



Figure 5.2 Availability factor (AF) across all years for Asset 1 and Asset 2

For Asset 1, availability remained consistently high at **99.8%** across 2022, 2023, and 2024, demonstrating a strong track record of operational reliability. These results demonstrate GOOREMALE's role in enhancing asset reliability, enabling proactive maintenance planning, and supporting long-term performance consistency across multiple geothermal assets. On the other result as seen in figure 5.2, the forced outage factor remained consistently low across all three years, ranging from **0.10% to 0.18%**, indicating a stable operation. The slight fluctuations are within acceptable limits and may be attributed to routine disturbances that were promptly mitigated through better visibility and faster RCFA processes. Overall, these improvements demonstrate that GOOREMALE played a critical role in reducing unplanned outages, enhancing equipment



Figure 5.3 Forced outage factor (FOF) across all years for Asset 1 and Asset 2

Financial indicators support the operational gains. As shown in Table 5.1, revenue deviation improved markedly. Moreover, the cost structure was effectively optimized: OPEX remained below target in both 2023 and 2024, and CAPEX was reduced substantially (–12% in 2023 and –69% in 2024). These improvements underscore the role of digital tools in enabling more informed and strategic capital and operational expenditure decisions.

Table 5.1 Revenue, CAPEX, and OPEX across 2022-2024

	2022	2023	2024
Revenue	Baseline	+9% refer from 2022	+11% refer from 2023
CAPEX	Baseline	-12% refer from 2022	-69% refer from 2023
OPEX	Baseline	+1.5% refer from 2022	+4.83% refer from 2023

In summary, the combination of digital transformation and machine learning under the GOOREMALE framework has proven to be a powerful strategy for improving geothermal operational optimization, reliability, and efficiency, ultimately supporting the achievement of corporate production and performance goals as seen in table 5.2.

Table 5. 2 Production, Availability Factor (AF), and Forced Outage Factor (FOF)
across all years

	2022	2023	2024
Production (Actual)	Baseline	+3.77% refer from 2022	+8.05% (2022) +4.12% (2023)
Production (Actual/Plan)	91.91%	98.21%	101.66%
Availability Factor (AF)	Baseline	+4.8% refer from 2022	+4.8% (2022) +0% (2023)
Forced Outage Factor (FOF)	Baseline	-70% refer from 2022	-84.2% (2022) -48.7% (2023)

5.2. Future Works

Building upon the successful implementation of GOOREMALE[®], several areas for future development are identified to further enhance the system's capability and impact.

The next step in the GOOREMALE initiative is to focus on the digitization of the subsurface model. This effort aims to centralize and streamline the management of geological, geophysical, and reservoir data in a digital format and real-time.

5.3 Recommendations

5.3.1 Development of an Automatically Updated Deliverability Curve Using Machine Learning, integrated to GOOREMALE

For operation aspect, digitization of the subsurface and reservoir data enables integrating machine learning models to dynamically generate and update the steam deliverability curve. This system could leverage thermodynamic parameters measured at the power plant—such as pressure, temperature, and mass flow rate—which are assumed to be more reliable due to higher sensor accuracy. By applying back-calculation techniques, the system can infer upstream performance conditions, including at the wellhead. Through iterative learning, the machine learning model

would not only validate current data but also continuously refine the deliverability curve, improving its accuracy over time and enabling more precise steam field management.

5.3.2 Advancement of Reliability Studies Through RAM and Weibull Analysis, integrated to GOOREMALE

As for reliability aspect, while this research has successfully introduced anomaly detection for early identification of equipment abnormalities, further advancements in reliability engineering are recommended. Future development should include comprehensive Reliability, Availability, and Maintainability (RAM) studies, supported by statistical modeling techniques such as Weibull analysis. This would enable more accurate failure forecasting, lifecycle assessment, and strategic maintenance planning, thereby enhancing the overall asset performance management framework.

5.3.3 Level 4 Roadmap Development

By 2028, The Level 4 – Support Executive Decision emphasizes the role of Artificial Intelligence (AI) in supporting executive decision-making, particularly for strategic areas such as O&M budget optimization, merit order optimization, lifecycle management (LCM) and maintenance strategy, as well as investment optimization. At this stage, decision-making is primarily executed by top management, including the Board of Directors (BOD) and Vice President (VP), with Decision Support System (DSS) tools providing comprehensive insights to enhance the quality, speed, and precision of these decisions. The inclusion of the new power generation unit that is planned to commercially operate in 2027 will expand the operational landscape, requiring the roadmap to account for higher complexity in asset coordination, maintenance prioritization, and investment planning. Therefore, embedding the new unit into the Level-4 framework ensures that strategic decision-making remains robust, data-driven, and aligned with long-term organizational growth.