D14.1: Risk assessment of OptiDrill drilling advisory system

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ACRONYMS

AI	Artificial Intelligence
ALARP	As Low As Reasonably Possible
BHA	Bottom Hole Assembly – The section of the drill string from the bit to the drill pipe. The BHA, is designed to include any specialised tools, technologies etc., that allow the well to be drilled efficiently.
DA	Data Analysis/Data Analytics
DDR	Daily Drilling Report – a record of all operations over a 12 or 24 hour period
DST	Drill Stem Test – operation where the pressure in the drill pipe is lowered, in order for gases/fluids from the formations can flow, for analysis
EOWR	End of Well Report – a full and final report on all activities associated with a well.
KPI	Key Performance Indicators
LCZ	Lost Circulation Zone – zones where the drilling flush is lost to the formation.
LTI	Lost Time Incident – loss of operational time (rig shut-down), usually due to personnel having an accident or a dangerous occurrence takes place that requires investigating.
LWD	Logging Whilst Drilling – in-hole equipment that logs formations being drilled
MD	Measured Depth – the total length of the well from surface to bottom
ML	Machine Learning
MWD	Measurement Whilst Drilling – records downhole data, azimuth, position etc as drilling progresses.
NPT	Non-Productive Time – all the time when the bit is not on the bottom of the well and drilling (May also include LTI).
OHAS	Operational Health and Safety
PP	Pore Pressure – Pressure due to compaction in the interstices of formations (Either fluids or gases). PP above hydrostatic may cause issues with drilling.
ROP	Rate of Penetration / Rate of Progress (This may either be “instantaneous drilling rate” or overall Time (Time/Depth plots)
RPM	Rotating speed of drill bit
TVD	True Vertical Depth – the depth difference from the top of the well to the base of the well, vertically, in order that hydrostatic pressure can be calculated for well control.
UCS	Unconfined Compressive Strength – Defines rock strength as derived from laboratory tests
WOB	Weight on Bit – the load applied to any drill bit to effect drilling

EXECUTIVE SUMMARY

This deliverable provides a comprehensive risk assessment for the OptiDrill project, supporting the development and deployment of advanced, data-driven drilling solutions for geothermal energy. As a key element of OptiDrill's project management, the risk assessment aims to proactively identify, evaluate, and mitigate factors that could impact the achievement of the project's technical, operational, and strategic objectives.

The risk management process in OptiDrill follows established best practices, integrating both qualitative and quantitative methods. Risk identification was undertaken through dedicated workshops, continuous partner engagement, and the analysis of project deliverables and external trends. All identified risks were systematically evaluated based on likelihood and impact, with prioritized risks subjected to deeper quantitative analysis, such as scenario and sensitivity assessments, to capture potential consequences and interdependencies.

The assessment highlights several principal risk categories, notably:

- Technological Risks: Challenges related to the integration and validation of novel digital drilling technologies in real-world geothermal projects.
- Operational Risks: Risks associated with field trial logistics, partner coordination, and the adaptation of OptiDrill solutions to diverse geological conditions.
- Regulatory and Market Risks: Uncertainties in permitting, compliance, and market uptake for geothermal innovations.
- Supply Chain and External Dependencies: Vulnerabilities in equipment supply, data acquisition, and reliance on external collaborators.

For each major risk area, targeted mitigation strategies have been developed, including enhanced technical validation, flexible deployment planning, active stakeholder engagement, and adaptive project management protocols. These measures are complemented by an ongoing risk monitoring process, with clear responsibilities, regular review cycles, and dynamic adjustment of risk registers as the project progresses.

Overall, the risk assessment establishes a robust foundation for informed decision-making and resilient project execution within OptiDrill. The proactive risk management approach described herein is designed to minimize adverse impacts, enhance the likelihood of project success, and ensure that OptiDrill delivers tangible value to the geothermal sector.

1. INTRODUCTION

OptiDrill is an ambitious European project dedicated to revolutionizing geothermal drilling through the application of advanced digitalization, real time data analytics, and innovative drilling technologies. Its mission is to enhance the efficiency, predictability, and overall impact of geothermal drilling, thus supporting the wider adoption of sustainable energy solutions across Europe.

Geothermal projects, by their very nature, present considerable complexity. The combination of challenging and uncertain subsurface conditions, the integration of new technologies, and the requirements of diverse and evolving regulatory frameworks make comprehensive risk management a fundamental necessity within OptiDrill. In this context, Occupational Health and Safety (OHAS) and environmental responsibility are not only legal imperatives but also core principles that underpin every aspect of the project.

OHAS and Health, Safety and Environmental (HSE) legislation have, over the past decades, shaped the way organizations manage risks. These laws are regularly updated and rigorously enforced, demanding that employers, manufacturers, and suppliers all ensure the highest possible standards of safety for people and the environment. It is not enough to comply only with the minimum legal requirements. Responsible organizations must embed risk awareness and safe practices in their culture, policies, and everyday operations. Every person involved has both the right and the responsibility to raise safety concerns without fear of prejudice or reprisal, and must remain vigilant to ensure that no task, however routine, puts people or the environment at risk.

Within OptiDrill, risk management is seen as a living, shared obligation that involves everyone in the project, from system designers and field operators to partners, suppliers, and stakeholders. Each operation and task are subject to careful risk assessment, mitigation planning, and targeted training. The project emphasizes the importance of regular review and communication of risks, making use of established practices such as toolbox talks, ongoing site inductions, and updates to Safe Systems of Work (SSoW). Where multiple operations occur in parallel or complex equipment is deployed, the need for well-coordinated risk management becomes even more critical to ensure that one activity does not inadvertently create hazards for another.

The digital transformation at the heart of OptiDrill brings new opportunities and responsibilities for risk management. The OptiDrill Drilling Advisory system, which operates as a real time decision support platform within drilling operations, reinforces safety by enabling constant monitoring, assessment, and adjustment of complex processes. The adoption of advanced digital tools, including machine learning and artificial intelligence, supports continuous compliance with safety standards and the rapid identification of potential risks or anomalies. However, it is recognized that these systems are not infallible, and analogue checks, inspections, and human oversight remain essential to maintain overall safety and compliance.

Complacency and lack of enforcement are among the greatest risks in any HSE context. OptiDrill addresses these challenges by promoting a culture of continuous learning, active participation, and robust enforcement of safety rules and procedures. The project not only seeks to meet current legislative requirements but also aims to set new benchmarks for responsible risk management in the geothermal sector.

This deliverable presents the structured risk assessment developed for OptiDrill, following internationally recognized standards and best practices. The assessment combines both qualitative and quantitative methods and draws on collaborative workshops, expert input, and detailed analysis of project activities. The objective is to identify and prioritize the full range of risks that could affect the project, including occupational health and safety, technical performance, environmental impacts, financial sustainability, and market acceptance. The findings are used to develop mitigation strategies and contingency plans that remain adaptable as the project progresses.

In addition to guiding project management, this risk assessment underscores OptiDrill's commitment to transparency, continuous improvement, and engagement with a broad community of stakeholders. The recommendations and strategies outlined here are designed to support the project consortium, funders, regulatory authorities, and the wider geothermal industry in managing both present and emerging risks.

This report introduces the risk management methodology adopted in OptiDrill, provides an overview of the risk identification and evaluation process, and describes the mitigation strategies and ongoing risk monitoring activities. The final section offers conclusions and recommendations for strengthening risk management in OptiDrill and in future geothermal initiatives.

By embedding a robust, adaptive, and participatory risk management framework rooted in both human vigilance and advanced digital technologies, OptiDrill is well positioned to meet the multifaceted challenges of geothermal innovation and create a lasting positive impact in the energy sector.

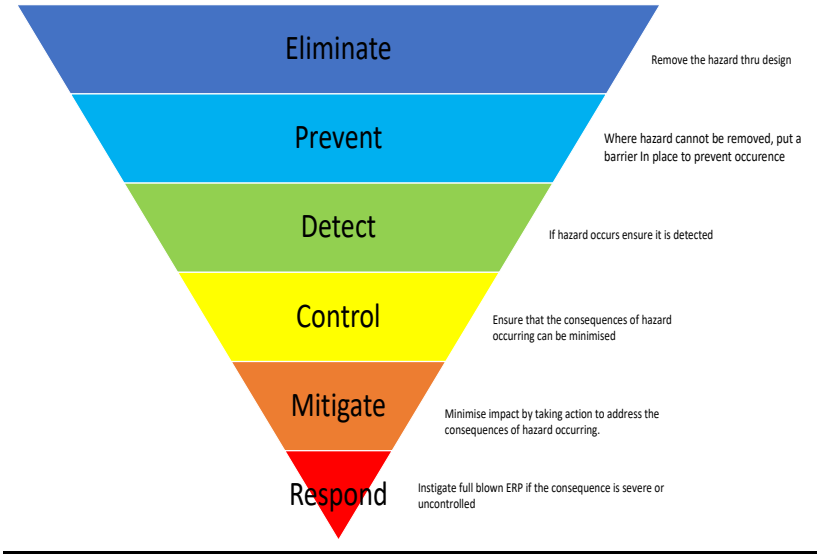

Figure 1 The Hierarchy of Risk Control Strategies

2. Methodology

Risk management in OptiDrill follows a structured approach that is based on international standards, especially ISO 31000, but is adapted to the real working conditions and requirements of a geothermal drilling project. The methodology combines both standard risk assessment practices and new solutions designed to fit the project's use of digital tools and field operations. The risk management approach in OptiDrill is structured to fit both recognized international standards and the unique needs of geothermal drilling projects. The methodology is based on the ISO 31000 standard and is designed to be practical and accessible to everyone working on the project, from field teams to management.

Risk Identification

Risks are identified at the start of each work package and again at important milestones or before field operations begin. OptiDrill holds dedicated risk workshops that include work package leaders, technical experts, field engineers, safety officers, and representatives from all project partners. When needed, specialists are invited, for example, a supplier expert when discussing the risk of equipment delays, or an environmental scientist during planning for drilling in protected areas.

For example, before the field demonstrations in the Upper Rhine Graben, a series of workshops brought together drilling engineers, digital system developers, and safety staff to list possible risks. The group considered factors such as unexpected rock formations, the need to install new sensors in harsh environments, and real time data transfer between remote drilling sites and the central project database.

Risk Scoring and Analysis

Once risks are listed, each is scored using a risk matrix. The group discusses each risk and agrees on a score for how likely it is to occur (from one for rare to five for very likely) and the severity of its impact if it does occur (from one for minor to five for critical). The scores are multiplied to get a risk rating, which is used to rank and prioritize risks. For example, the risk of sudden equipment failure in a high temperature well was rated as high, due to both a realistic chance of occurrence and the serious impact on safety and project progress.

Both qualitative and quantitative techniques are used. Qualitative assessment includes drawing on the knowledge and experience of the group, while quantitative tools such as scenario analysis or sensitivity analysis are used for key risks. In one case, a scenario analysis estimated how a two-week customs delay for a drilling sensor shipment could delay overall site operations and increase costs.

Mitigation and Action Planning

For each significant risk, specific actions are planned. A risk owner is assigned, usually the person or partner best placed to address the risk. Mitigation actions can range from design improvements to backup equipment procurement or updates to staff training. During OptiDrill's live field operations, for example, the risk of high-pressure blowouts was addressed by revising standard operating procedures, upgrading personal protective equipment, and organizing additional training on emergency response for all personnel on site.

The risk register records each risk, its owner, the planned mitigation, progress updates, and review dates. This register is a living document, updated after every major project meeting or whenever a new risk is identified.

Ongoing Monitoring and Communication

Risks and mitigation plans are reviewed regularly at project meetings and whenever there are changes in the project environment. All project partners can access the current risk register, and changes are communicated quickly. This was particularly important during the COVID-19 pandemic, when new local health and safety rules required fast updates to site working procedures and risk controls.

Practical Application in OptiDrill

The risk management process has already proved valuable in several OptiDrill activities. For example, during the integration of the Drilling Advisory System, the risk of data loss was identified and addressed by introducing automatic data backups and regular software checks. In another case, a supply chain disruption was managed by arranging a backup supplier and keeping key parts in stock at the drilling site. These actions have helped reduce project delays and improve safety during drilling operations.

The OptiDrill methodology for risk management is designed to be clear, hands on, and responsive. It is built on open communication, active participation from all partners, and the use of both traditional and digital risk management tools. By keeping risk management practical and connected to daily work, OptiDrill aims to protect both its people and its project results.

3. Risk Identification and Evaluation

The risk identification and evaluation process in OptiDrill was carried out in close coordination with all project partners, using a combination of technical meetings, dedicated workshops, and regular reviews throughout the project timeline. This process was designed to ensure that all known, anticipated, and emerging risks were captured and assessed in a systematic way.

Risks identified during the project have been grouped into several main categories, each reflecting the specific challenges faced by the consortium:

Technical Risks:

These include risks related to the development, integration, and operation of the OptiDrill Drilling Advisory system. Examples are the risk of malfunction or underperformance of the system, issues with data quality from sensors, and the challenge of adapting software to different drilling environments and data interfaces.

Operational Risks:

Operational risks focus on project scheduling, logistics, and the deployment of equipment and digital infrastructure. Coordination among partners, management of field activities, and supply chain reliability have all been monitored as potential sources of operational risk.

Health, Safety, and Environmental Risks:

The health and safety of personnel remain a top priority. Risks identified here include the exposure of field staff to hazardous conditions, handling and installation of equipment, and the potential impact on the environment during field activities. The project ensured that site access procedures, emergency response protocols, and safety instructions were regularly updated in response to changing conditions.

Regulatory and Compliance Risks:

This includes the risk of delays in obtaining necessary permits or approvals, as well as changes in national or European regulations that could affect project execution. The consortium maintained regular communication with regulatory bodies to minimize these risks.

Financial Risks:

These relate to the potential for cost overruns, budget uncertainties, or delays affecting project funding and milestones.

Each risk was assessed for its likelihood and potential impact using the risk matrix described in the methodology. High priority risks were assigned owners and closely monitored, with specific mitigation measures identified and implemented as needed.

A complete register of identified risks, along with their assessment and assigned actions, has been maintained and regularly updated throughout the project. This systematic approach enabled the consortium to address critical risks proactively and to adapt to new challenges as they arose.

Further details on unique, system-specific risks associated with the OptiDrill Drilling Advisory system and its components are presented in the following section.

3.1 THE OPTIDRILL SYSTEM

The OptiDrill system is a complex, modular platform combining hardware (such as downhole sensors and surface equipment), digital infrastructure, AI-based advisory software, real time data acquisition, and integration with existing drilling rigs and operational practices. Each subsystem presents its own set of risks, which must be addressed at both component and integrated system levels. The project has undertaken a structured assessment of these risks, based on real project experience, operational feedback, and technical evaluation.

1. Hardware Risks (Sensors, Surface Equipment, Connections)

Downhole Sensors and Electronics

- Mechanical failure or loss of sensor components in the well, leading to non-retrievable parts, risk of well blockage, or damage to other drilling tools.
- Heat and pressure damage during extended downhole deployment, potentially causing loss of data, inaccurate readings, or shortened sensor lifespan.
- Ingress of drilling fluids or improper sealing, compromising electronics or data cables.
- Physical handling risks, such as weight-related injuries, splinters, or failures at lifting/installation (see previous detailed section).

Surface Data Acquisition and Communication Equipment

- Environmental exposure (temperature, dust, vibration, moisture) affecting laptops, communication boxes, and power supplies.
- Unstable surface conditions during rig-up/rig-down, with risk of trip hazards, equipment falls, or electrical accidents.
- Cable management, where improper layout or protection of Ethernet/datalink cables can lead to damage, data loss, or trip risks for personnel.

2. Digital and Software Risks

AI Software and Advisory Algorithms

- Incorrect advisory outputs due to incomplete input data, misconfiguration, or unexpected downhole conditions, potentially leading to wrong operational decisions.
- Software bugs or crashes that interrupt data acquisition, storage, or real time analytics.
- Version control and update risks, where software upgrades may introduce new incompatibilities or unanticipated behaviors, especially in live field conditions.

Data Acquisition, Integrity, and Cybersecurity

- Data loss during real time acquisition due to signal dropouts, storage failure, or buffer overflows.
- Data corruption from electromagnetic interference or improper shutdowns.
- Cybersecurity threats, including unauthorized access, malware, or data theft from remote connections or USB devices used on site.
- Compatibility and integration risks between OptiDrill's digital platform and existing rig instrumentation or operator IT networks.

3. Integration and Operational Risks

Integration with Drilling Rigs and Field Procedures

- Incompatibility between OptiDrill and third-party rig equipment, leading to improper data handshakes or lack of real time advisory feedback.
- Interruption of drilling workflow due to integration or troubleshooting activities.
- Dependency on specialized personnel for installation, operation, or troubleshooting, with risk of knowledge gaps or unavailability during critical periods.

Training, Human Factors, and Change Management

- Insufficient training of field personnel in the safe and correct use of new hardware and digital interfaces.
- User errors in data entry, system configuration, or response to advisory recommendations.
- Resistance to new procedures from rig crews accustomed to traditional methods, leading to inconsistent application of OptiDrill solutions.

Health, Safety, and Environmental Aspects

- Exposure to hazardous conditions when installing or troubleshooting equipment in active drilling sites.
- Failure to follow updated safety procedures specific to digital system use (such as "lockout-tagout" for electronic equipment).
- Environmental risk from accidental fuel or lubricant spills associated with the operation or maintenance of OptiDrill components, and the management of electronic waste at end-of-life.

4. Data Lifecycle, Maintenance, and Sustainability

- End-of-life management for electronic and steel components, requiring clear protocols for recovery, disposal, and recycling in line with sustainability goals.
- Long-term data storage and privacy, especially regarding operational data that may have commercial sensitivity or personal information.
- Sustainability risks if component or consumable use outpaces project recycling or environmental targets.

5. Regulatory and Compliance

- Alignment with local and international standards for drilling operations, digital systems in critical infrastructure, and data protection.
- Changes in regulatory environment affecting permissible equipment, software deployment, or data handling at drilling sites.
- Permit requirements for field deployments, especially when new digital or sensor systems are introduced at regulated locations.

Table 1 System-Specific Risk Assessment: The OptiDrill System

Risk Area	Example Risks	Mitigation / Control Measures
Hardware (Sensors & Surface Equipment)	Sensor or electronic failure; loss of parts in the well; physical injury from heavy/lifting; heat/pressure damage; cable damage; environmental exposure of laptops.	Use purpose-designed lifting/handling tools; non-destructive testing; regular inspections; weather-protected cases; PPE; clear cable management; compliance with rig standards.
Digital Platform & Software	Incorrect advisory output; software bugs/crashes; data loss/corruption; version conflicts; cyber threats; integration failures with rig systems.	Regular software validation and updates; robust backup routines; user access controls; cyber policies; compatibility testing before deployment; clear update protocols.

Operational & Integration	Rig system incompatibility; workflow interruptions; dependence on specialists; delays from troubleshooting; supply chain delays for spares or upgrades.	Early integration testing; documentation of procedures; cross-training; maintaining spare parts inventory; strong supplier engagement; redundancy in key roles.
Human Factors & Training	Insufficient training; user errors in configuration or response; resistance to adoption of new workflows; misunderstanding of system alerts.	Comprehensive training; user manuals; on-site support during rollout; feedback sessions; active change management; regular drills and refresher courses.
Health, Safety & Environment	Exposure during equipment setup; improper lockout/tagout for electronics; accidental spills; risks during troubleshooting in hazardous zones; improper e-waste disposal.	Field-specific safety briefings; standard operating procedures; PPE; spill response kits; certified e-waste recycling protocols; regular audits of compliance.
Lifecycle & Sustainability	Lack of recycling for electronics/metals; unsustainable component use; unmanaged end-of-life waste; long-term data retention/privacy risks.	Lifecycle planning for all hardware; vendor take-back agreements; data archiving/deletion policies; compliance with environmental and data protection regulations.

To fully understand the risks associated with the OptiDrill system, they will be broken down into component sections, detail unique risk profiles as well as industrial and regulatory benchmarks/requirements, to ensure all or any risks are addressed accordingly. The risks of the system are minimal, but still require identifying and controlling, for operational safety, which includes risks to health (short, medium & long term) as well as the risks of potential physical harm.

The environmental risks posed by the OptiDrill system, are minimal, but as part of an overall drilling operation to exploit geothermal resources, then these risks increase exponentially and can only be assessed as an integrated study of the impacts. However, geothermal energy is seen as hugely important to reaching net-zero energy goals, related to carbon emissions and, therefore, needs to be included in the understanding of any impacts.

As the downhole sensors are contained within a machined, heat-treated steel short pipe, which is inserted within the BHA, there are a number of inherent risks, as well as risks introduced by the installation of the downhole sensor section:

The OptiDrill system introduces a new set of risks that extend beyond traditional drilling hazards, covering advanced hardware, digital platforms, integration processes, and human factors. These risks have been documented, evaluated, and integrated into the overall project RAMS. Continuous review, targeted mitigation, and open communication with field and management personnel are used to ensure that both system-specific and overall project risks are controlled to the lowest practicable level.

The OptiDrill system will eventually require third-party safety validation, provided by a company such as DNV or RINA, whereby standards are set to ensure that the system and products within the system, can be safely incorporated into an operating system and SSoW.

Figure 2 OptiDrill Data and Decision Workflow

The DSE will be purchased from proprietary manufacturers, produced in accordance with international standards, and operated in accordance with the manufacturer's instructions and national legislation (e.g. operating periods, repetitive stress injuries etc.). All other proprietary items, such as cables, sensors will also meet required standards and the whole OptiDrill system fully compliant and integrated.

All operators/end-users of the OptiDrill system will undergo full OHAS training of the system and how the system will be incorporated into an overall Risk Assessment & Method Statement (Mitigation Strategy) – RAMS. Some of these RAMS will be generic, but also operational and site-specific requirements.

The OptiDrill system will work alongside the rig's operating and safety systems it will not override or interfere with any of the rig's functions, this will remain the prerogative of the operator/driller, even where some functions are automated (e.g. load sensing hydraulic systems).

Drilling operations are subject to strict and rigorous safety and environmental conditions and the utilisation of the OptiDrill system will be incorporated into the OHAS/HSE.

3.2 Risk Mitigation and Monitoring

The OptiDrill project follows a practical, dynamic approach to risk mitigation and ongoing risk monitoring. The goal is to ensure that all significant risks whether technical, operational, digital, or HSE-related are controlled to the lowest practicable level throughout every phase of the project.

3.2.1 Risk Mitigation Strategies

For each major risk identified in the assessment process, specific mitigation measures have been developed, implemented, and tracked. These strategies have been adapted over time in response to field experience, feedback from partners, and changes in the operating environment. Some of the main approaches are summarized below:

Technical Risks:

Regular inspection, calibration, and non-destructive testing of hardware components reduce the chance of mechanical or electronic failure. Preventive maintenance schedules and the use of proven, field-tested components have been prioritized. Spare parts and backup systems are kept on hand for rapid response in the event of failures.

Digital Platform and Data Risks:

The project enforces strict version control for all software, with thorough validation before deployment. Automatic data backup routines, real time system monitoring, and periodic audits of data integrity are standard practice. Cybersecurity measures including user access controls, and regular updates are in place to protect against data loss or unauthorized access.

Operational and Integration Risks:

Early-stage integration tests are performed with drilling contractors and rig operators to resolve compatibility issues. Installation and troubleshooting guides are prepared for each deployment. Key roles are cross-trained so that critical knowledge is not limited to a single individual. Partnerships with suppliers and contractors include clear communication channels and escalation plans for potential disruptions.

Human Factors and Training:

All field personnel receive detailed training on the safe handling and correct use of OptiDrill equipment and software. Training materials include user manuals, hands-on sessions, and refresher courses. On-site support is provided during initial deployments, and feedback from crews is used to improve procedures and materials.

Health, Safety, and Environment:

Site-specific risk assessments are prepared for each field operation, with emphasis on integrating digital and hardware-specific controls into established safety practices. PPE requirements, emergency response plans, and environmental protection protocols are updated as needed. Incident reporting systems are in place to capture near-misses and actual incidents, supporting a culture of learning and continuous improvement.

The OptiDrill System poses minimal environmental risks, and these would be evaluated for each operational site within the Environmental Impact Assessment, required as part of a geothermal resource well (or wells) planning application.

Artificial Intelligence – Risks and Impacts

AI is defined as a computer or algorithm capable of carrying out tasks that are perceived to require varying levels of intelligence, depending upon the complexity of the task. For example, a simple task would be separating square wooden blocks from round ones. A complex task would be identifying cancerous cells amongst healthy cells.

AI is widely accepted as the new 'industrial revolution' and its usage amongst all sectors of industry and business operations is rapidly increasing, but as with all things that require to be taught (be it humans or machines) the quality of material used to educate is vitally important to the outcomes. Therefore, the volume and fidelity of training data used by the OptiDrill advisory system needs to be controlled, and as with all AI based systems the efficacy of the system will increase. There will of course be early-stage anomalies within the system, but as it is advisory for drilling teams and not for automating all operations, the risks of hazardous mistakes being made are minimised.

Lifecycle and Sustainability:

The project has developed guidelines for the responsible disposal and recycling of end-of-life components. Vendor agreements and documentation requirements help ensure that materials are tracked and recovered wherever possible.

All components and materials used within the OptiDrill system are recyclable, within national capabilities. In regions where suitable recycling facilities are not available components may be shipped to the nearest facility, utilising transport with a minimal carbon footprint (e.g. Electric Vehicles).

Estimated operational lifetimes of OptiDrill system components are:

- **Sensor Strings** - < 2,000 hours (operating hours as recorded). Fully recyclable.
- **Computers/DSE** – 5 years, subject to hardware capability and updates. Fully recyclable.
- **Interconnects** – 5 years, subject to possible damage. Fully recyclable.

Regulatory and Compliance:

The consortium maintains regular contact with relevant regulatory authorities. Legal and standards reviews are conducted before every major field deployment to confirm compliance, and the system architecture is kept flexible to accommodate evolving requirements.

3.2.2 Ongoing Monitoring and Review

Risk management in OptiDrill is not a one-time activity. Risks and mitigation measures are tracked continuously in a central risk register, which is reviewed and updated at each project management meeting and after any significant incident or operational change.

All partners have access to the latest risk register and are encouraged to propose new risks, report observations, and suggest additional controls at any time. This open, participatory approach helps capture new risks early and ensures that controls remain effective as the project evolves.

When high-priority or unexpected risks emerge such as changes in field site access, unplanned equipment failures, or new health regulations, immediate action is taken. Mitigation strategies are reviewed, and new controls are implemented as needed.

Through these processes, OptiDrill maintains a high level of readiness to manage risks and to respond quickly to challenges, supporting both the safe delivery of project objectives and continuous improvement in drilling operations.

4. Conclusions and Future work

The risk assessment and management approach used in the OptiDrill project has been essential for supporting safe, efficient, and innovative geothermal drilling. By systematically identifying and addressing risks at every level, from specific equipment hazards to broader operational and digital system challenges, the consortium has been able to anticipate issues and ensure that project objectives are met.

Occupational Health and Safety (OHAS) is a continuously changing field. It evolves with new legislation, lessons learned from incidents and accidents, and the adoption of new technologies while older ones are phased out. With AI at the core of the OptiDrill system, the importance of ongoing learning and adaptation becomes clear. Effective risk management must not only address immediate hazards, but also keep pace with changes in technology, regulations, and best practices.

Throughout the project, open communication, regular risk reviews, and close collaboration among all partners have enabled the early identification and treatment of both technical and operational risks. The project has shown that ongoing improvement, careful documentation, and responsive controls are essential for managing the risks associated with innovation, especially as digital and AI-driven systems become central to operations in the field.

Looking to the future, further integration of the OptiDrill system with other advanced technologies in drilling operations represents a natural next step. Possible areas for development include:

- Connecting with advanced wellhead geological chip logging systems, such as those that use X-ray diffraction and spectroscopy.
- Integrating with preventative maintenance systems to enable more proactive care for equipment.
- Enhancing inspection and testing programmes by linking digital data from multiple sources.
- Enabling data sharing with daily drilling records, including analysis of lost time incidents and other key events.

Expanding the scope of system integration and participating in global data sharing will help increase the adoption and success rate of geothermal projects. By bringing together information from different systems, OptiDrill can support reductions in both capital and operational costs, foster learning, and encourage wider adoption of geothermal energy technologies.

Recommendations for ongoing and future work are as follows:

- Maintain and update the central risk register with regular input from all partners.
- Further develop training programmes for both field operations and digital systems, ensuring that new staff and partners can work effectively with AI-driven tools.
- Keep strong relationships with regulatory authorities and design systems to adapt quickly to changing compliance requirements.
- Build procedures for responsible end of life management, sustainability tracking, and recycling of both hardware and digital components.
- Encourage a culture of open reporting, continuous learning, and shared responsibility for risk management.
- Pursue new opportunities for linking OptiDrill with additional data sources, field equipment, and knowledge sharing networks across the industry.

OptiDrill has established a strong standard for proactive and practical risk management in geothermal drilling. The lessons and methods developed in this project provide a solid foundation for future digital innovation, ensuring that safety, sustainability, and efficiency remain central goals in geothermal operations.