

Blockchain-based Decentralized Digitalization of the Prominent Geothermal District Heating System Services

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Abstract—The digitalization of mainstream services in critical energy infrastructures and major industrial processes has become increasingly essential and has accelerated in recent years. Among various district heating options, geothermal-sourced district heating networks offer a cleaner pathway toward a low-carbon future, especially when compared to systems based on coal-fired boilers, natural gas, waste heat recovery, waste-to-energy, biomass, or oil-fired boilers, all of which produce significant emissions. In the context of emerging 4th and 5th generation (4G and 5G) heating systems, decentralized digitalization plays a central role, and blockchain technology holds significant potential to support this transformation. This study explores key services within geothermal-sourced district heating networks that can be primarily digitalized using blockchain-based platforms. The study also provides valuable insights for the smart contracts, functions, and stakeholder/user authorization tailored to these

services.

Keywords—Blockchain, Digitalization, Geothermal District Heating, Smart Contracts, Decentralized Energy Systems

I. INTRODUCTION

Digitalization across sectors like energy, manufacturing, healthcare, finance, and transportation has accelerated since the 2010s due to technological advances, economic pressures, regulatory demands, and societal expectations. Key drivers include cloud and edge computing for faster processing, IoT for real-time monitoring, AI/ML for automation, blockchain for secure transactions, and advanced communication networks (e.g., 4G/5G). These innovations make digital solutions technically feasible and economically viable.

The push for decarbonization and sustainability, driven by policies like the EU Green Deal [1] and the Paris Agreement [2], increases the demand for energy efficiency and cleaner energy integration, further spurring digitalization efforts. Ad-

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ditionally, data protection laws [3], customer expectations for personalization and transparency, and the need for resilience and cybersecurity all drive digitization.

The Geothermal District Heating (GDH) market in Europe has grown to \$6.3 billion, with a 7.8% CAGR projected until 2033 [4]. Municipal systems like Klaipėda and Ball State University are adopting geothermal solutions for sustainable heating. However, conventional GDH systems face challenges such as temperature/pressure decline, scaling/corrosion, heat losses, and maintenance issues due to lack of real-time data.

4th and 5th generation district heating (4G/5G) concepts are gaining attention, focusing on energy efficiency and utilizing renewable sources [5]. 4G systems aim to reduce heat losses through lower temperature levels, while 5G operates near-ground temperatures with bidirectional heat exchangers and seasonal storage.

Digitalization and smart control enable these advanced systems, with blockchain offering potential to improve data integrity and security in decentralized geothermal systems. A 2018 study at KTH identified 32 blockchain applications in district heating [6], but the literature on blockchain for geothermal district heating is still limited.

This study explores blockchain applications for monitoring, operations, and reporting in geothermal district heating systems. It identifies and prioritizes key services, proposing smart contract structures and platform functions for stakeholder management. The findings contribute to the development of blockchain-based monitoring platforms for geothermal district heating.

The paper is structured as follows: Section 2 provides a literature review, Section 3 outlines the methodology, Section 4 presents the case study and findings, and Section 5 concludes with recommendations for future research.

II. STATE OF THE ART

In the related literature, the term Web 3.0, or Web3 is used for the next evolution on the internet. Compared to today's centralized, IT companies owned data, servers and cloud computing in Web 2.0, decentralized, user-owned data and assets are aimed to be securely governed and controlled by community-driven consensus protocols, where decisions are made collectively by stakeholders in Web 3.0.

Web 3.0 is positioned to play a crucial role in Industry 4.0, with its decentralized, user-controlled and highly secure features [7]. Blockchain is a foundational technology for Web 3.0, as it enables its core principles, including decentralization, security and ownership.

Blockchain has recently been shaping the mobility ecosystem, through the activities ongoing under "Mobility Open Blockchain Initiative (MOBI)" [8], which has major automotive manufacturers, IT companies, and some other mobility ecosystem major stakeholders. The members co-develop standards, conduct field pilots on blockchain integration into wide range of mobility ecosystem processes.

There also have been adoption efforts of blockchain in the aviation industry [9]. The domains such as passenger veri-

fication, in-flight entertainment, automated secure invoicing, digital identity, distribution and payment, real-time baggage and cargos tracking, securing customer loyalty programs, digitizing crew verification and other are considered to be suitable services that can be digitized [10].

Blockchain integration has also been thoroughly investigated in the maritime industry [11]. Use cases like, lading billing, ship operations, maritime insurance, ship finance, logistics tracking are considered to be digitized and handled in blockchain-based platforms.

Blockchain application areas suitable for district heating companies in district heating systems are primarily investigated in [6], prioritizing metering and maintenance quality assurance, enhancing signing, storing and sharing of documents for administrative processes, simplify communication between stakeholders, ensure confidentiality and integrity of data among many others. Another study [12] examines green IT innovations for district heating, proposing a technology platform with user-friendly interfaces, connecting the company's production and customers' substations in real-time. [13] provides a different perspective, by categorizing district heating digitalization according to end use/consumption, infrastructure, system and business processes. A comprehensive report [14] prepared by International Energy Agency (IEA), District Heating and Cooling (DHC) technology collaboration programme in 2023, investigates the current state-of-the-art in operational optimization of production, distribution, at consumer level, analytics for fault and leak detection, predictive maintenance and system improvement, and forecasting.

Besides the efforts listed in the mentioned studies mainly about district heating digitalization, or blockchain integration into different sectors in the previous paragraphs of this section, there have not been sufficient investigation of digitalization of geothermal district heating. Moreover, even the existing studies have not discussed the tailored smart contracts, related platform functions and authorization of the stakeholders in sufficient details.

This paper contributes to the expanding body of knowledge in this area of study by,

- identifying prominent use cases for geothermal district heating systems,
- designing smart contract structures and functions tailored for each use case,
- determining role-based access control (RBAC) and authorization for each use case,

as a whole, which can considerably foster backend development activities of blockchain-based monitoring, operation and reporting platforms for geothermal district heating.

III. METHODOLOGY

The methodology adopted in this study involves four key steps: (1) identifying and prioritizing use cases for both the geothermal source and the district heating network; (2) determining the parameters to be monitored; (3) designing use case-specific smart contract structures and functions; and (4) defining platform user roles aligned with stakeholders,

including the authorization of actions and permissions for each role. This is a sector-agnostic approach that can be replicated or repeated in different sectors for especially blockchain-based digitalization activities.

The first step, involves understanding the specific challenges and conventional activities, and opportunities of using blockchain technology in geothermal source and in district heating. Following identification, the prioritization is done depending on the potential of blockchain to improve operational efficiency, transparency, and data integrity, taking into account feasibility, potential impact and cost-effectiveness.

The second step, investigate which parameters need to be tracked in real-time and recorded to blockchain specific to prioritized each use case. The third step, develops which processes can be automated through smart contracts and the related platform functions, considering aspects such as ensuring transparency, minimizing the risk of fraud or human error, handling governance, ensuring compliance with regulatory standards.

The last step, step four, is on combination of policy-based RBAC, fine-grained RBAC, and separation of duties (SoD) to represent a highly flexible and secure access control system, providing more comprehensive and nuanced control over user access in environments with complex workflows and high security requirements.

IV. CASE STUDY

The case study details are presented under two subsections, distinguishing activities related to geothermal source and district heating, respectively.

A. Blockchain-based Digitalization of Geothermal Source

Geothermal source asset management fields, each of their subfields and the prioritized subfields are listed in Table I. Reservoir Monitoring, Maintenance, Environmental Regulations, Health and Safety, and Reporting are selected as they are the fundamental activities that are even critical for the conventional systems and can be primarily digitalized, while some of the others are the emerging subfields that can be considered in further digitalization activities at later stages. The primary parameters that need to be monitored for the selected use cases are given in Table II.

For reservoir management, sensor readings can be stored using the smart contract format determined in Table III. A supportive parameter, reservoir section is determined to allow for different handling of readings and thresholds for different parts of the reservoir (such as near the production well, at reinjection point, wellhead, deep zone and other subsurface monitoring points). Apart from the fundamental parameter each sensor is used for, additional, accompanying side-parameters can be provided by sensors available in the market, and data slicing can be used to store multiple number of sensor accompanying parameters dynamically. The smart contract data storing format for storing thresholds for different parameters measured at different sections of the reservoir is given in Table IV. Similar data storing format and functions can be used for district

TABLE I.
GEOTHERMAL SOURCE ASSET MANAGEMENT

Main Field	Subfield
Resource Assessment and Monitoring	Reservoir Monitoring*, Geological and Geophysical Surveys, Digital Twin Technology
Operational Efficiency	Maintenance*, SCADA Systems, Performance Optimization
Asset Life-Cycle Management	Drilling and Well Management, Equipment Upgrades, Decommissioning
Financial and Risk Management	Cost Management, Insurance and Risk Management, Investment Strategies
Regulatory Compliance and Reporting	Environmental Regulations*, Health and Safety*, Reporting*

*The prioritized subfields.

TABLE II.
GEOTHERMAL SOURCE PARAMETERS

Parameter	Unit
Drilled water temperature	°C
Drilled water flow rate	m ³ /h
Well pressure	bar
Reserve water level	m
Reserve temperature	°C
Chemical components in reserve	ppm
Equipment (production well pump, compressor and/or heat exchanger) vibration	mm/s
Equipment (production well pump, compressor and/or heat exchanger) temperature	°C
Equipment (production well pump, compressor and/or heat exchanger) pressure	bar

heating network sensors, with only the “Reservoir Section” field is replaced with “Heat Network Section”. The essential functions related to reservoir management are determined as in Table V. The maintenance log entry format is provided in Table VI.

The essential functions for maintenance are determined as in Table VII. The essential functions related to environmental regulations related to geothermal source are determined as in Table VIII. For environmental regulations use case of district heating, the same functions can be utilized. The functions for health and safety can be found in Table IX. The fundamental functions for reporting are given in Table X. The reporting functions identified for geothermal source can also be used for district heating reporting purposes.

The stakeholders related to the identified geothermal source use cases are shown in Figure 1.

The blockchain network and smart contract-chain code developer has the admin role, responsible of full management of the platform, determining and editing smart contracts, managing the roles and authorizations of other network participants, oversight of validity of data, encryption and security. Field personnel has access to all operational data, monitored system parameters and maintenance records. Energy generation, temperature, flow rate and similar measurements are monitored in real-time and their records are added to the network under the responsibility of field personnel accounts. The owner organization of the source has access to periodic reports that summarize energy generation, system performance and financial records. The regulatory compliance inspection organizations has access to limited data related to only reg-

TABLE III.
RESERVOIR DATA SENSOR READINGS STORING FORMAT

Parameter	Data Type
SensorID	string
ReservoirSection	string
Owner	string
Timestamp	string
FundamentalParameter	float64
AdditionalParameterQuantity	string array
AdditionalParameter-1	float64
AdditionalParameter-2	float64
-	-
-	-
AdditionalParameter-n	float64

TABLE IV.
RESERVOIR SECTION THRESHOLDS STORING FORMAT

Parameter	Data Type
Reservoir section	string
TemperatureMax	float64
PressureMax	float64
FlowRateMin	float64
WaterLevelMax	float64
WaterLevelMin	float64
VibrationMax	float64
Owner	string
Operator	string

TABLE V.
RESERVOIR MANAGEMENT ESSENTIAL FUNCTIONS

Function Name	Description
StoreSensorReading	Records real-time sensor measurements
GetLatestReading	Retrieves the most recent reading
GetSensorHistory	Returns past readings for a time period
SetThresholds	Sets thresholds and monitoring resolution
CheckThresholds	Compares real-time data with thresholds
GenerateAlert	Sends an alert when abnormality detected
GetAlertHistory	Returns past alerts for a time period
AssignToSection	Links a sensor to a specific section
AssignToOwner	Links a sensor to a network participant that can read
AssignToOperator	Links a sensor to a network participant that has editing right

TABLE VI.
MAINTENANCE LOG ENTRY FORMAT

Parameter	Data Type
MaintenanceRecordID	string
ReservoirID	float64
ReservoirSection	float64
Tasks	float64
Status	float64
Cost	float64
Timestamp	float64

TABLE VII.
MAINTENANCE ESSENTIAL FUNCTIONS

Function Name	Description
LogMaintenanceTasks	Record maintenance tasks (inspection, cleaning, repair and other)
ScheduleMaintenance	Schedule a new maintenance
CheckMaintenanceHistory	Retrieve past logs
GenerateMaintenanceAlert	Automatically request maintenance due to alerts
ApproveMaintenanceRequest	Approve maintenance plans before execution

TABLE VIII.
ENVIRONMENTAL REGULATIONS ESSENTIAL FUNCTIONS

Function Name	Description
LogEmissionData	Record GHG, particulate emissions
SetEmissionThresholds	Set regulatory limits for GHG
CheckEmissionCompliance	Compare data with the thresholds
MonitorGroundwaterQuality	Log water quality parameters
ScheduleInspection	Approve maintenance plans before execution
LogInspection	Store regulatory inspection details
GetInspectionLogs	Return past logs for a time period
IssueEmissionAlert	Send alert for limit violation
GetEmissionAlertLogs	Return past alerts for a time period

TABLE IX.
HEALTH AND SAFETY ESSENTIAL FUNCTIONS

Function Name	Description
LogSafetyIncident	Record incident and near-misses
MonitorHazardousGas	Track hazardous gases in worker zones
SetGasExposureLimits	Define safety limits for hazardous gases
CheckGasExposure	Compare real-time data with the limits
IssueSafetyAlert	Send alert in case of limit violation
ScheduleSafetyInspection	Schedule site audit
LogSafetyInspection	Store inspection details
GetInspectionLogs	Return past logs for a time period
GetSafetyAlertLogs	Return past alerts for a time period

TABLE X.
REPORTING ESSENTIAL FUNCTIONS

Function Name	Description
GenerateEmissionReport	Creates report using GHG records
GenerateEnvImpReport	Create report using groundwater, air quality and waste heat discharge
GenerateOpReport	Create report based on power output, well status, and equipment health
GenerateSafetyReport	Create report based on incidents
GenerateFinancialReport	Create report on sales, costs and expenses
GetPastReport	Return past reports for a time period for a report type
SetReportingPeriod	Create report using GHG data

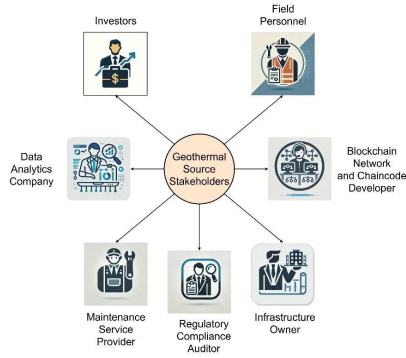


Fig. 1. The stakeholders related to the geothermal source.

ulatory compliance procedures, compliance reports and past measurement viewing authorization. Investors are allowed to view limited financial and operational data. Energy generation and obtained revenue, financial reports (on such as investment payback, cost of generation), uninterrupted operation of the system and performance metrics can be viewed by this stakeholder type. Maintenance service providers are able to view system state-related data and create maintenance-repair logs. Equipment failures, operational abnormalities and problems viewing, and failure-repair related notification viewing permissions are covered for this stakeholder group.

B. Blockchain-based Digitalization of District Heating Network

District heating use cases are provided in Table XI. The prioritized subfields are selected based on their applicability and importance.

As mentioned in the previous section, the sensor data storing format and threshold storing format can be easily employed for similar district heating network processes, by only changing “Reservoir Section” as “Heat Network Section”. Environmental regulations and reporting data storing formats determined for geothermal source can also be used for district heat network similar use cases. The functions for leak detection, water loss monitoring, hydraulic balance monitoring, and district heating network stability are provided in Table XIII.

The stakeholders for district heating use cases are given in Figure 2.

The blockchain network and smart contract-chain code developer has the admin role, responsible of full management of the platform, determining and editing smart contracts, managing the roles and authorizations of other network participants, oversight of validity of data, encryption and security.

District heating grid operator has access to all operational data, monitored system parameters and maintenance records. Inlet and outlet temperature, pressure, flow rate, distribution losses and similar measurements are monitored in real-time and their records are added to the network under the responsibility of operator account.

The regulatory compliance inspection organizations has access to limited data related to only regulatory compliance

TABLE XI.
DISTRICT HEATING USE CASES

Main Field	Subfield
Network Infrastructure and Pipeline Monitoring	Pipeline Temperature and Pressure Monitoring*; Leak Detection and Water Loss Monitoring*; Flow Rate and Hydraulic Balance Monitoring*; Pipe Corrosion and Aging Detection
Substation and Consumer Interface Monitoring	Heat Exchanger Efficiency Monitoring; Smart Metering and Consumption Analytics*
Regulatory Compliance and Reporting	Environmental Regulations*; District Heating Grid Stability Monitoring*; Reporting*

*The prioritized subfields.

The parameters that need to be monitored are listed in Table XII.

TABLE XII.
DISTRICT HEATING PARAMETERS

Parameter	Unit
Supply flow rate	m ³ /h
Return flow rate	m ³ /h
Flow distribution across the network	m ³ /h
Supply temperature	°C
Return temperature	°C
Temperature difference (ΔT) between supply and return lines	°C
Building-level temperatures at consumer premises	°C
Supply line pressure	bar
Return line pressure	bar
Overall demand of the network	kW or MW
Valve position	% or binary 0/1
Pump speed	RPM
Pump power demand	kW
Pump vibration	mm/s

procedures, compliance reports and past measurement viewing authorization. Investors are allowed to view limited financial and operational data. Heat consumption and obtained revenue, financial reports (on such as investment payback, cost of heating), uninterrupted operation of the system and performance metrics can be viewed by this stakeholder type.

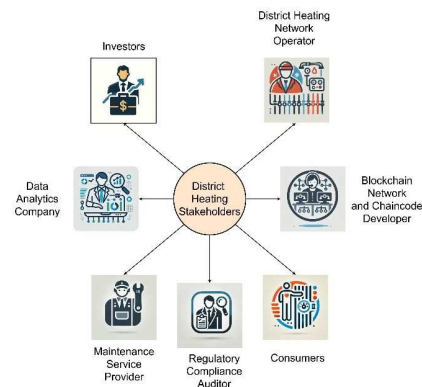


Fig. 2. The stakeholders related to the geothermal source.

Maintenance service providers are able to view system state-related data and create maintenance-repair logs. Equipment

TABLE XIII.

LEAK DETECTION, WATER LOSS MONITORING, HYDRAULIC BALANCE MONITORING, AND DISTRICT HEATING NETWORK STABILITY MONITORING ESSENTIAL FUNCTIONS

Function Name	Description
MonitorTemperatureVariations	Track temperature drops to detect pipe leaks
MonitorPressureDrop	Tracks unexpected pressure losses due to leaks or blockages
MonitorWaterLoss	Tracks water loss due to leaks
MonitorHydraulicBalance	Tracks real-time flow rates and pressure drops across the heat network
MonitorPumpInstability	Tracks underperforming or overcompensating pumps
SetAlertThresholds	Sets thresholds for detection for the regularly monitored parameters and monitoring periods
CheckDetectionThreshold	Compares real-time data with the thresholds
GetPastData	Returns past logs for a determined time period for a determined parameter
IssueDetectionAlert	Sends alert in case of threshold violations
GetDetectionAlertLogs	Returns past alerts for a determined time period

Smart metering and consumption analytics related fundamental functions are provided in Table XIV.

TABLE XIV

SMART METERING AND CONSUMPTION ANALYTICS ESSENTIAL FUNCTIONS

Function Name	Description
ReadMeter	Records real-time heat consumption data from smart meters
SetTariffRates	Defines pricing for heating based on consumption tiers
GenerateBill	Computes bills based on energy use and tariffs
GetPastConsumption	Return past meter logs and bills for a determined time period

failures, operational abnormalities and problems viewing, and failure-repair related notification viewing permissions are covered for this stakeholder group.

Consumers are authorized to view real-time temperature measurement and historical heat consumption data related to only their building sections.

V. CONCLUSIONS

This study presented one of the pioneering efforts to design a blockchain-based digital platform framework for monitoring, operation, and reporting of geothermal district heating systems. By systematically identifying and prioritizing use cases for both geothermal sources and district heating networks, the study established a detailed foundation for how decentralized technologies can be effectively leveraged to enhance transparency, reliability, and automation within critical thermal energy infrastructures.

For the geothermal source domain, five key use cases were prioritized and investigated. Correspondingly, seven major use

cases for district heating networks were prioritized. For each use case, specific smart contract structures, sensor parameters, and essential platform functions were defined, along with clear stakeholder roles and authorization hierarchies based on role-based access control principles. Future work will focus on the real-world implementation of the proposed platform, through edge IoT devices that support multiple protocols used by the sensors that will be preferred in the field, addressing scalability through multi-channel and forking, data privacy through hierarchical role-based access control (RBAC) and attribute-based access control (ABAC), and cost implications improvement through off-chain storage.

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