

Executive Summary

Croatian Hydrocarbon Agency (CHA) is planning to implement GT-CCS Bockovac project that represents a pioneering effort to integrate carbon capture and storage (CCS) with geothermal energy production in the Drava Depression of eastern Croatia. Therefore, CHA and SLB contracted preparation of an integrated feasibility study for the permanent disposal of CO₂ in an aquifer at the Bockovac site, with a specific focus on the implementation of a combined Geothermal–Carbon Capture and Storage (GT-CCS) concept (this Study).

The ultimate purpose of the study is to define a robust development concept that is:

- Economically viable – ensuring competitive project economics and scalable implementation
- Environmentally safe – guaranteeing long-term containment integrity and minimal environmental impact
- Technically and operationally feasible – supported by sound reservoir engineering, well design, and surface integration

The project is articulated in three phases:

- *Phase 1* focuses on transport and storage engineering, starting with an introductory analysis of the CO₂ emitters, transport options, and regulatory framework ([1 Introduction](#)) and following with detailed subsurface characterization for CCS and geothermal site selection ([2 Geological and reservoir engineering solution](#)) and the CO₂ transport and injection system design ([3 Elaboration of the transport system](#)).
- *Phase 2* covers the remainder of the surface facility engineering, notably the design of CO₂ injector wells ([4 CO₂ injection system](#)) as well as of a geothermal doublet and power plant ([5 Geothermal Energy Generation System](#))
- *Phase 3* consists of the analysis of the safety aspects of the project and of the design of a monitoring plan (described together in [6 Security, monitoring and tracking measures](#))

Finally, the cost and schedule of the project are summarized in [7 Project Execution and Cost Estimates](#), and conclusions are summarized in [8 Conclusions](#).

Chapter 1: Introduction

The project's foundation rests on a spatial and technical analysis of Croatia's major CO₂ emitters (1.1-1.2), with the Bockovac Area of Interest near the Eastern cluster of industrial sources. The largest local emitter, a cement plant, generates over 600,000 tons of CO₂ annually and is situated merely 35 kilometers from the planned injection site. This proximity, together with the presence of existing natural gas pipelines, provides logistical advantage for CO₂ transport. A comparative review of CO₂ transport methods finds that pipelines are the preferred approach for large volumes; the proposed approach is to purpose-build CO₂ pipelines along the existing rights of way, although repurposing the existing pipelines could be considered. Benchmarking of CO₂ stream compositions (purity, water, oxygen, impurities) shows that the CO₂ stream aligns with international

standards; special attention should be given to minimizing water and oxygen content to prevent corrosion and maximize transport safety. The findings demonstrate that the Bockovac Area and regional emitters have a feasible pathway for CCS integration.

Croatia's legal framework for CCS (1.3) is harmonized with European Union standards and provides a robust context for this undertaking. The permitting process in the Bockovac area is enabled by the region's extensive geological data and relatively few ecological or regulatory challenges. This places Bockovac in a favorable position for integrated CCS and geothermal development that supports the country's energy transition aims.

Chapter 2: Geological and reservoir engineering solution

The geological survey of the Bockovac area reveals a complex but promising subsurface, shaped by tectonic and sedimentation processes. Leveraging data from dozens of wells, seismic interpretation, and historical documentation, the study identified productive intervals exhibiting dual porosity systems and, in some instances, oil and gas accumulations. Based on seismic interpretation, petrophysical data analysis and well correlation, a detailed geological model was built, providing a consistent and reliable reservoir characterization for ongoing CCS and geothermal feasibility.

The seismic interpretation study (2.2) integrated seismic-to-well ties, attribute analysis, fault and horizon mapping, and time-to-depth conversion, focusing on key stratigraphic horizons: Alfa, B, C, D, Z', Rs7, and Tg. The interpretation delivered time-domain structural maps and an initial velocity model for time-to-depth conversion, identifying two main fault families contributing to structural complexity and compartmentalization.

Petrophysical analysis (2.3) focused on 16 selected wells with high-quality logs, which enabled the assessment of shale volume (Vsh), effective porosity, and permeability, as well as the identification of storage and containment units and the determination of formation temperatures, crucial for the geothermal potential. The well correlation study (2.4) documented the vertical and lateral stratigraphic relationships across the area of interest, using log markers and lithological descriptions to correlate key reservoir and seal intervals and mapping lateral facies variability. An initial geomechanical assessment (2.6) was also carried out, focusing on determining safe injection pressure limits for CCS.

The geological model of the area (2.5) was divided into two zones, the upper section (Alpha to Z horizon) and the more structurally complex lower zone (below Z), to improve grid integrity. Property modeling was performed for shale volume, porosity, permeability, temperature, and pressure, as well as lithology modeling. Volumetric estimations and reserves ranking used distinct strategies for the upper and lower zones, focusing on net thickness and area calculations.

The site selection for CCS operations (2.7) was rigorously benchmarked for technical and regulatory compliance. Storage capacities were estimated to be between 15 and 21 million metric tons of CO₂, with annual injectivity requirements shaping the evaluation. Reservoirs were selected at depths needed to maintain supercritical CO₂, with suitable containment performance, while sites

near residential or protected zones were avoided to reduce health, safety, and environmental risks. Volumetric analysis and chance-of-success mapping helped pinpoint optimal locations, resulting in three top-ranked sites, respectively near Bockovci-1, Magadenovac-1 and Camagajevci-1 well, all exploiting multiple target formations to maximize storage capacity.

Detailed CO₂ injection simulations (2.8), built on the integrated reservoir model, focused on 3 candidate sites in the Karas Suma-Bockovci area. The optimal scenario uses four deviated injection wells to store approximately 19 million tons of CO₂ over thirty years in the Karas Suma site. Simulation results show stable reservoir pressure, effective plume confinement, and trapping mechanisms that promote long-term security. Recommendations are provided to further build confidence in storage performance, notably containment.

The geothermal site selection and feasibility study (2.9) focuses on the deep geological horizons (Rs5, Rs7, and Pn), with a stacked-reservoir approach to increase the chances of intersecting productive intervals. Two key development areas were identified: the Rasovac and the Bockovci AOI, with more favorable subsurface conditions and surface constraints respectively. The study details the uncertainties, including limited well test and chemistry data; fluid geochemistry analyses (2.10) indicated variability in water and gas compositions, with possible scaling and corrosion risks.

Long-term simulations (2.10) confirmed technical feasibility for geothermal doublets in both AOIs, enabling sustained production rates of 80 liters per second over 30 years. Minimum production temperatures remained above 148°C in Rasovac and 152°C in Bockovci, supported by favorable characteristics of the lower Pn formation.

Chapter 3: Elaboration of the transport system

Surface facility design connects the main emitter (cement plant) to the storage site through a pipeline network that follows existing infrastructure corridors. The project's surface facilities requirements are structured around three main pillars: safe and effective injection at the reservoir level, optimal wellhead conditions and well configuration, and secure transport of CO₂ from the emission source to the storage site. The development targets a base injection rate of 0.636 million tons per annum (MTPA) over a 30-year operational period, with each well assigned a specific injection rate based on reservoir characteristics.

The pipeline network is routed primarily along existing natural gas infrastructure, minimizing environmental impact and avoiding population centers and protected zones such as Natura 2000 areas. The flowline is 37 kilometers long, buried to a depth of 1.5 meters, and is designed to operate without insulation. A 304.8-mm (12-in) internal diameter (ID) offers greater flexibility for handling surges or increased volumes. The elevation profile reduces pressure losses and compression requirements.

Well modeling established the optimal tubing size at 76 mm ID (3 in), balancing the need for lower injection wellhead pressures and erosional velocity ratios against cost. Injectivity improves as CO₂ displaces water over time. The pressure drop across the perforations is significant, primarily due to

fluid cooling in the reservoir, but the system remains safely outside hydrate formation conditions. Multiple operational scenarios were simulated, including variations in pipeline diameter, ambient temperature, and CO₂ purity.

Energy requirements for the system include compression of CO₂ to approximately 100 bar at the source, with heat exchangers cooling the fluid to 40°C before pipeline entry. Several scenarios were run, resulting in requirements between 1.9 and 2.8 MW for the expected outlet pressure at the emitter.

Compressor power and heat exchanger duty were calculated for various scenarios, ensuring that all rotating equipment is electrically driven and power is sourced from the grid. The system overview confirms that the design avoids hydrate formation and two-phase flow under all modeled conditions.

Chapter 4: CO₂ injection system

The CO₂ borehole system employs four deviated J-type CO₂ injector wells, KS1 to 4, drilled from a shared pad to access deep reservoir formations beneath the Karas Suma protected forest area, with surface infrastructure carefully placed outside the reserve to comply with environmental regulations. The design process included schematics, stress and hydraulic calculations, and preliminary cost analysis, centering on the KS4 well, which serves as a template for other injectors. Key engineering challenges highlighted are managing reservoir pressure during injection, addressing the long-term effects of CO₂ on well integrity, and selecting suitable materials such as CO₂-resistant cements and premium alloys for casing and completion equipment.

Well trajectories were chosen to minimize environmental impact, and the plan incorporates rigorous stress and load assessments to ensure structural durability throughout the well lifecycle. The proposed casing and cementing strategies are tailored to guarantee zonal isolation and prevent CO₂ migration, with water-based muds used for drilling. The estimated drilling time for KS4 is about 45 days, and extensive data acquisition is planned for the first well drilled on the site. A preliminary budget for KS4 stands at €10 million, spanning all major operational and material requirements. Recommendations for future work are provided, including further subsurface data collection, expansion of engineering analyses to dynamic scenarios and laboratory confirmation of materials.

Chapter 5: Geothermal Energy Generation System

The conceptual design for the Rasovac geothermal plant features two J-profile wells, one injector and one producer, positioned so that all key surface infrastructure avoids encroaching on protected areas. Pressure estimates from KS4 well plan inform the drilling plan, mud weight selection, and casing design to ensure borehole stability and controlled operations. The casing plan includes several strings, engineered for strength against high temperature and various stress scenarios, with appropriate material choices and derating for thermal loads. Drilling fluid programs are outlined for each section. The estimated drilling time for the Rasovac Injector is about 49 days,

including mobilization and demobilization, with a similar schedule for the Producer well. Data acquisition plans are proposed to improve the characterization of the geothermal system. The plan accommodates non-productive time and contingencies.

Electricity production from geothermal resources at Rasovac is planned using an Organic Rankine Cycle (ORC) power plant. This system is modeled for summer, winter, and annual operating conditions, with its air-cooled condenser specifically optimized for hot summer periods. Forecasts suggest gross output fluctuates seasonally between 1.9 and 3.3 megawatts, with a net annual export of approximately 1.8 gigawatt-hours to the grid after accounting for internal consumption. Notably, modeling confirmed there is no hydraulic connection between the CO₂ and geothermal reservoirs, so CO₂ injection will not compromise power output.

Chapter 6: Security, monitoring and tracking measures

Chapter 6 of this study presents a thorough framework for managing risk, security, monitoring, and tracking measures at the Bockovac CO₂ storage and geothermal project. The approach integrates international best practices and Croatian regulatory standards, with a structured methodology for identifying, evaluating, mitigating, and continuously tracking risks throughout the project's lifecycle. Risks are appraised using multiple criteria—financial, scheduling, reputational, environmental, legal, cost, and rated for likelihood and severity. Critical risk categories include storage site containment and performance, well integrity, environmental protection, and legal and social concerns.

A detailed, site-specific monitoring and tracking plan is provided, covering subsurface and surface tracking of CO₂ operations. Controls span fault and seal analysis, geomechanical surveys, core integration, high-resolution seismic, robust well design, rigorous cementing and monitoring, laboratory testing, and real-time pressure surveillance. Environmental risks are addressed through baseline water sampling and comprehensive monitoring of both surface and subsurface conditions, supported by health monitoring and rapid response protocols. Project governance outlines clear responsibilities, with risk ownership shifting to the operator as the project advances. Adaptive management features prominently, with ongoing data acquisition, stakeholder engagement, and regulatory compliance supporting continual refinement of risk assessments.

Chapter 7: Project execution and cost estimates

The capital cost estimate for the realization of this project amounts to 225 million euros for the CCS component and 28.5 million euros for the geothermal component.

In particular, for the CCS facilities, 21 MEUR are estimated for the site exploration and appraisal; 153 MEUR for the project execution (construction) (of which 58 MEUR are estimated for transport, 39 MEUR for surface facilities, 41 for the injection wells and 15 for the injection site); 13 MEUR for project maturation (concept definition FEED and FID); and 39 MEUR for the monitoring plan implementation. Operative costs of 19.95 MEUR per year are estimated, inclusive of monitoring.

The estimated capital cost of the geothermal component amounts to 17.7 MEUR for the well doublet and 10.8 MEUR for the surface facilities (power plant).



Chapter 8: Conclusions

In conclusion, the Bockovac CCS & Geothermal Project is a technically, environmentally, and strategically robust initiative. Its integrated approach combines geological opportunity with sound engineering and responsible risk management, establishing a model for sustainable decarbonization and renewable energy production in Croatia and the broader region.