GEO-COAT

DEVELOPMENT OF NOVEL AND COST-EFFECTIVE CORROSION RESISTANT COATINGS
FOR HIGH TEMPERATURE GEOTHERMAL APPLICATIONS

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D9.1: Impact of Geo-Coat application on LCOE

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PU – Public (e.g. on website, for publication etc.) / **PP** – Restricted to other programme participants (incl. Commission services) /
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02	25/05/2021	Mohammad Ashadul Hoque	• Replaced Icelandic case study (ICS) with Icelandic perspective (IP) and Romanian case study (RCS) with Romanian perspective (RP) • Removed reference of Iceland and Romania from summary • Instead of 1st and 2nd ranked coatings only best ranked coating • Updated Eq 3-a to 3-b for better readability • LCOE results for IP and RP • LCOE instead of misspelled LCEO • Python source for cost factor calculation

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Executive Summary

The aggressive environment of medium to high temperature geothermal resources makes geothermal plant components vulnerable to corrosion, erosion and scaling, which is a challenge in maintaining the integrity of the various plant components. To combat aggressive geofluids in future geothermal project development, the Geo-Coat project proposes cost-effective anticorrosion, anti-scaling coating materials (Geo-Coat technology) for low-cost carbon steel (CS) substrates as an alternative to the state of art (SOA) materials with the aim of providing improved component performance during the lifetime of the plants. Determining the economic impacts of these Geo-Coat substrate materials, coating materials and the deposition processes is an essential step in designing a green, sustainable technology for geothermal components. In this study, the economic impacts of the Geo-Coat technology adopted for geothermal components have been evaluated along with SOA materials utilising LCOE (levelised cost of energy) methodology. One double flash and one binary type geothermal power plant have been considered for the evaluation of economic impacts with and without adoption of Geo-Coat technology for pipes, turbine rotors, blades and well casings. We have already ranked Geo-Coat technologies per application area using the laboratory results of the corrosion, tribological and cost performances and the recommended weightings of these performances. The double flash and the binary geothermal power plant, with the adoption of the best ranked Geo-Coat technology instead of SOA materials, give a LCOE reduction of 91% and 26% respectively. The results of this study illustrate the sustainable nature of Geo-Coat technology for geothermal components.

Objectives met:

The current deliverable contributes towards the following work package objective:

- To demonstrate the potentialities of Geo-Coat to improve the economic performance of the geothermal power.

CONTENTS

1 INTRODUCTION

High temperature and pressure conditions of geothermal resources and the corrosive nature of geofluid pose a significant threat to maintaining the integrity of geothermal components such as pipes, turbine components, well casings, and pump impellers. Corrosion, erosion and scale formation or combinations of these can occur in these components at different locations of geothermal power plants. To obtain higher enthalpy geofluid for increased output of geothermal systems, deeper wells are needed. Geothermal environments become more aggressive in deep wells and hence the increased corrosion, erosion and scaling effects put the efficiency and longevity of the plant components at risk. Several countries such as Iceland, New Zealand, Philippines, Indonesia, Kenya, Uganda, Mexico and US have carried out research activities to combat aggressive geofluid for future geothermal project development[2]. These studies proposed use of expensive and corrosion resistant materials such as stainless steels 630SS, A470, 304L, titanium alloys, etc as state of art (SOA) materials for different geothermal components. But the use of such materials will require huge investment and thereby will make future deep geothermal projects less economically viable. It is proposed that the use of Geo-Coat technologies for different geothermal components instead of using SOA materials will enhance the growth of geothermal power.

The Geo-Coat project has developed novel coatings and metal matrix composite (MMC) component systems (Geo-Coat technologies) for six geothermal application areas: i) pipes and casings (S1), ii) valve stem & turbine blades (S2), iii) turbine rotors (S3), iv) turbine blades (S4), v) pump impellers (S5), and heat exchanger tubes (S6). The overall ranking of Geo-Coat technologies per application area has been evaluated based on laboratory-scale results of the corrosion, tribological and cost performances, considering the weightings of different performances as suggested by the advisory board, experts in geothermal energy within the Geo-Coat consortium. One Geo-Coat technologies (best ranked Geo-Coat systems) have been selected for each of the six geothermal application areas and are listed in ***Table 1-a.***

***Table 1-a**: Best Ranked Geo-Coat technologies for each application area*

Substrates	Application areas	Best ranked Geo-Coat system
S1	Pipes & casings	LC_HEA2
S2	Valve stem & turbine blades	LC_HEA2
S3	Turbine rotors	LC_HEA2
S4	Turbine blades	LC_HEA2
S5	Pump impellers	HIP_Ti64+10% TiB_2
S6	Heat exchanger tubes	Undercoat: High P%; Topcoat: Low P%, 10 g/l PTFE, no HT (ENP41_DC)

Under Geo-Coat WP6, WEIR has performed erosion-corrosion tests for down-selected ranked systems using FEC (free erosion-corrosion) and cathodic protection (CP) method with 3.5% NaCl concentration and 4 pH level simulated environment. The results indicated that the LC_HEA2 coating system showed the greatest erosion-corrosion resistance. Flow-through corrosion, static corrosion and stress corrosion cracking exposure tests with simulated geothermal environment was carried out in WP6 for down-selected coating systems for each substrate/application. In WP8, the well-head and aerated pressure vessel tests (Test A) and erosion-corrosion (Test C) field were carried out. Erosion-wear, scratch test and three-point bend tests are also being carried after static corrosion (WP6) and Test A exposure field tests (WP8).

The Geo-Coat substrate (GCS) materials were selected as a cheaper alternative, with a lower environmental impact, compared with the proposed SOA materials, with the aim of providing improved component performance. The Geo-Coat project has selected five Geo-Coat substrate materials (S1:S235JR, S2:316SS, S3:1.2746, S4:304L and S6:S235JR) where the selected Geo-Coat coatings will be applied. The pipe and well

[2] R P Houser, Performance of eleven Ti alloys in high temperature, high pressure brine solution; Proc. World Geothermal Congress 2010.

casing component materials (S1) such as stainless steel 630SS, 316L, carbon steel S235JR or P265GH, K-55, etc, are currently being used at different locations of the pipe network of geothermal power plants worldwide. The SOA materials of either CrMoV steel or 2% Cr Steel or A470 steel for turbine rotors (S3) are being used. Ti alloys are highly resistant to localised corrosion and stress corrosion cracking in the presence of chlorides, halides, or halogens, and to hot highly acidic solutions[3], whereas most carbon steels, stainless steels and Ni-based alloys show poor performance. Ti alloys are also recognised for their high resistance to erosion and erosion-corrosion, which is an important characteristic in areas of the geothermal plant where high-flow geothermal fluid is found. For the above reasons, Ti alloys have been recommended for use in turbine blades and well casings as SOA materials[4]. For economic impact studies with Icelandic and Romanian perspectives, the materials 630SS, Ti-6Al-4V, A470, and Ti-6Al-4V have been considered for the pipes, well casings, turbine rotors, and blades respectively – referred to as SOA systems. ***Table 1-b*** lists the SOA materials employed for pipes, turbine rotors, blades and well casing components.

Table 1-b: SOA materials considerations for geothermal components of well casings, pipes and turbines

SOA ID	Application areas	SOA materials employed for Icelandic (IP) and Romanian case (RP) studies	Adjusted SOA materials for LCOE studies	Geo-Coat proposed SOA materials
S1	Well casings	IP: K-55 RP: P265GH	Ti-6Al-4V	P265GH
S1	Pipes	IP: S235JR & 316L RP: P265GH	630SS	P265GH
S3	Turbine rotors	IP: low alloy steel CrMoV	A470	A470
S4	Turbine blades	IP: stainless steel (17-4PH for last stage)	Ti-6Al-4V	304L

For maintaining the integrity of the pipe, turbine and well casings during the lifetime of the plant, it is recommended to use Geo-Coat substrates coated with the best Geo-Coat coatings (LC_HEA2) – referred to as Geo-Coat technologies/systems, as alternatives to SOA systems in future geothermal power plants.

For comparisons of economic impacts with and without adoption of Geo-Coat systems, i.e. Geo-Coat technology, the pipes (S1), turbine (S3-S4) components and well casings (S1) have been considered for the case studies from Icelandic and Romanian perspective. For these comparative economic impact studies, we have used the best ranked Geo-Coat systems for well casings, pipes, turbine rotors, blades and pump impellers listed in ***Table 1-c***.

Table 1-c: Best ranked Geo-coat systems for different application areas of the geothermal power plants

Well casings (S1)	Pipes (S1)	Turbine rotors (S3)	Turbine blades (S4)	Pump Impellers (S5)
LC_HEA2_S235JR	LC_HEA2_S235JR	LC_HEA2_1.2746	LC_HEA2_304L	HIP_Ti64+10% TiB2

For comparative LCOE studies with and without adoption of Geo-Coat technology, two hypothetical power plants bases on the double flash type 303MW Hellisheiði, and the binary type 50kW Transgex-Oradea geothermal power plants have been considered and these are referred to as the Icelandic perspective (IP) and the Romanian perspective (RP), respectively. The economic impact assessment for the geothermal components (well casings, pipes, turbine rotors and blades) employed in IP and RP plants with and without the adoption of the best ranked Geo-Coat systems (***Table 1-c***) have been carried out using the TVS geothermal LCOE calculator.

[3] J. Niogara and S. J. Zarrouk, "Corrosion in geothermal environment Part 2: Metals and alloys," Renewable and Sustainable Energy Reviews, vol. 82, pp. 1347-1363, 2018.
[4] S. N. Karlsdottir, "Corrosion, scaling and material selection in geothermal power production," in Comprehensive renewable energy, Elsevier, 2012, pp. 241-259

The details of the LCOE methodology are described in Section 2, Section 3 presents the comparative LCOE studies with and without the adoption of Geo-Coat technology for the case studies from Icelandic and Romanian perspective after evaluation of all economic impacts. LCOE results on economic impact due to the adoption of the best ranked Geo-Coat systems are concluded and given in Section 4.

2 METHODOLOGY

0The levelised cost of energy (LCOE) estimates the representative cost of generating electrical power from a power plant over its lifetime and is used to compare different methods of electricity generation on a consistent basis. LCOE is the ratio between all the discounted costs over the lifetime of a power plant divided by a discounted sum of the actual energy delivered. In other words, LCOE is the average revenue per unit of electricity (in €/kW-hr or €/MWh) that would be required for a power plant to break even. LCOE estimation are dependent upon factors specific to the scenario being evaluated, with most of these factors defined by user inputs.

For the Geo-Coat project, we have developed a LCOE framework based on the GETEM and GEOPHIRES LCOE calculators. During the development, we have modified several design and cost parameters of the GETEM LCOE calculators. We have also considered some methods from the GEOPHIRES LCOE calculator such as levelised cost of heat (LCOH) models, different levelised cost models etc, that are appropriate for the Geo-Coat project. GETEM, originally developed for the Department of Energy's Geothermal Technologies Program (GTP), is a method for estimation of the cost of power generation from geothermal energy, and a means of assessing how technology advances might impact generation cost, determined as LCOE. The entire framework of the Geo-Coat LCOE calculator, in general, considers the different components and functionality of a full-scale geothermal plant. Because the Geo-Coat project only considers some components of a geothermal plant, the economic impact of Geo-Coat innovations has been estimated keeping the cost of other components unchanged.

Geo-Coat LCOE estimation considerers all phases of geothermal project development, with a unique duration and discount rate applied to each. They are:

1. Exploration
   - Permitting
   - Non-drilling exploration activities
   - Drilling small-diameter holes
   - Drilling full sized wells to confirm viability
2. Develop project to the point necessary for power purchase agreement (PPA)
   - Drilling full-sized wells to develop necessary capacity for PPA
   - Installation of field gathering system for wells
   - Power purchase agreement
3. Complete project development once PPA is obtained
   - Complete development of well fields
   - Complete installation of field gathering system
   - Installation of geothermal pumps
   - Plant construction
   - Transmission line construction
4. Operation and maintenance
   - Labour
   - Plant maintenance
   - Filed maintenance
   - Royalties
   - Taxes & insurance

Costs are estimated for the activities in each project phase, along with the estimated power generation over the plant lifetime, to provide the basis for the LCOE estimate.

LCOE input data for the two case studies have been collected from Geo-coat partners and literature study. However, due to lack of complete datasets, in this study we have chosen to perform LCOE estimates on geothermal plants based on the plants data have been collected from, but not exactly the same. We have used as much data as available for the case studies, and for the remaining input parameters we have used GETEM defaults. This approach still provides us with a suitable comparison of the Geo-Coat technologies.

In this study, LCOE estimation is based on the number of production wells. Once the project size is determined, the capital and operating costs are estimated. The well field characterisation assumes that the production or injection wells are identical. Production wells all have the same depth, casing configuration, flow rate, temperature, and productivity index. The injection wells are similarly identical. The estimate of power generation over plant lifetime is based on the premise that the resource temperature declines with time, while the geothermal flow rate remains same. To account for the impact of resource temperature decline, the power sales are predicted at monthly intervals and determined for each period based on the temperature decline. Makeup drilling will occur if the temperature decline is excessive and the production temperature is assumed to return to the initial value.

Capital Costs:

Geo-Coat LCOE calculator considers the capital cost for all the phases geothermal project development described above. The capital costs included in the determination of an LCOE are summarised in ***Figure 2-a***.

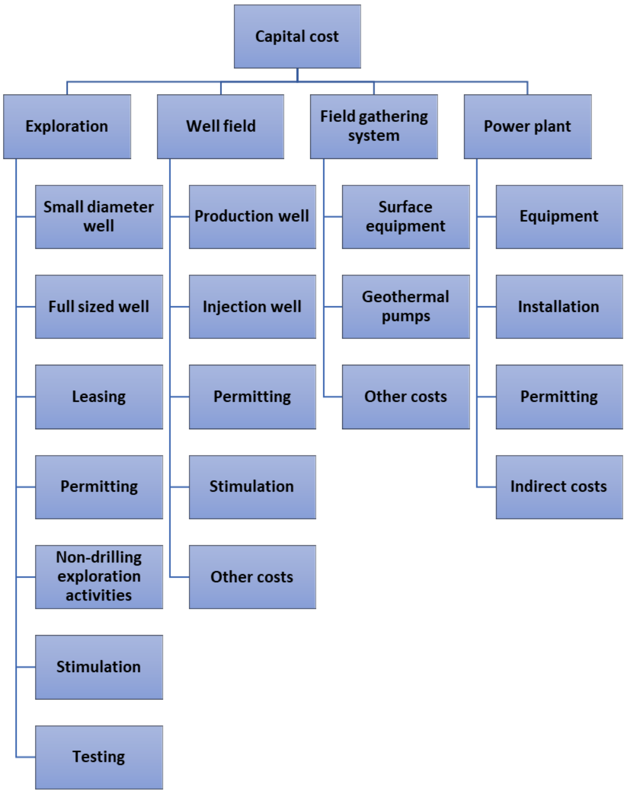

***Figure 2-a**: Capital costs for LCOE estimation*

A contingency of 15% is applied to all capital cost in the LCOE estimation. Costs for full-size well drilling is the exception to this; the correlations used to estimate well costs include a contingency term. In Geo-Coat LCOE estimation a discounted cash flow (DCF) methodology is used. The present value of costs and revenues are determined at start-up using specified discount rates (***Table 2-a***) for each phase of the project. In this study we have not considered any incentives that may be available for the geothermal sector.

***Table 2-a**: Economic parameters used for LCOE estimation*

	Parameter	Value
General Project Variables	Contingency	15.00%
	Royalty (thru Yr 10)	1.75%
	Royalty (after Yr 10)	3.50%
	Discount Rate During Operation	7.00%

	Effective Tax Rate	39.20%
	Net Capacity Factor	95.00%
	Project Life (Period of Operation)	30 yr(s)
Pre-Operation Discount Rates	Exploration	7%
	Drilling (including Stimulation)	7%
	Field Gathering System	7%
	Plant Construction & Start-up	7%
Project Schedule & Durations	Exploration	2 yr(s)
	Drilling	2.5 yr(s)
	Field Gathering System duration	2.5 yr(s)
	Plant Design & Finalising PPA	1 yr(s)
	Plant Construction & Start-up	1.5 yr(s)

***Table 2-b**: Permitting parameters used for LCOE estimation*

Parameter	Value
Duration of Permitting for Exploration & Early Drilling Activities, years	0.5
Permitting Costs for Pre-Drilling Activities per site	€45,814
Permitting Costs for Drilling - Exploration & Early Drilling per site	€114,535
Duration of Permitting for Plant/Field (Utilisation Permit), years	0.75
Utilisation Permit Cost for Well Field & Power Plant	€916,280

Exploration:

To simplify estimation in this study we have considered greenfield projects only. This is also justified by the fact that in both case study sites corrosion and erosion are not major concerns, and hence Geo-Coat technologies are not in demand. It is assumed that multiple prospects will need to be evaluated and drilled to develop a successful project. It is also assumed that full-size wells at one or more sites will need to be drilled to verify commercial potential. In this study we have not considered exploration costs as a function of size of the project. Also, default costs are based only on those incurred at the successful site, which include initial exploration activities, permitting and leasing, drilling of small diameter wells, and the drilling and testing of a limited number of full-size wells to establish that the resource is commercially viable.

Drilling:

In this study, the number of production wells for the case studies comes as an input. Production well flow rate, total flow injected and the ratio of the production to injection well flow rates (default value 0.75) are used to determine the required number of injection wells. Drilling cost is estimated from the well depth. In this study we have assumed that all production and injection wells have the same depth and cost regardless of whether they are successful or not. A drilling success rate (75%) is used to determine how many wells mut be drilled to get the required number of production and injection wells. Though we have considered that unsuccessful production wells will be used to supplement injection resulting in a reduction in the required number of successful injection wells. Permitting, testing and indirect costs such as engineering, management etc are considered in total drilling costs. This study assumes that 60% of the total field capacity must be developed to obtain a PPA. In this study well stimulation was not considered.

Geofluid gathering system:

Geofluid gathering system cost is based on the number of wells. Each well has an associated cost for surface equipment, which is determined using the average distance between plant and well and pipe size. If a production pump is used then pump setting, depth and size in horsepower (hp) are based on the casing configuration, flow rate, well depth, geofluid temperature and the productivity index. Similarly, cost associated with an injection well is determined, except for the injection pump which is assumed to be in a single location. The total cost of the geofluid gathering system is the sum of surface equipment and pumps. In addition, the total geofluid gathering system included an indirect cost that is 12% of the total cost.

Power plant:

Depending upon plant type, i.e. binary or flash, two different methods are used for power plant capital costs. The capital cost of a binary plant is based on resource temperature, plant size and specific plant output. Binary power plant equipment costs are estimated from the second law efficiency, which is determined from specific plant output and resource temperature. The equipment costs for the binary plant therefore vary directly with this second law efficiency, i.e. a more efficient plant may have higher plant equipment costs, but will need less flow, fewer wells, less geothermal pumping power etc. To get the minimum LCOE a trade-off between plant efficiency and cost is therefore required. But, to get a like-to-like comparison between state-of-the-art and Geo-Coat technologies, in this study, this optimisation was not performed. Flash power plant costs and performance estimates are based on flash pressures that are determined using a built-in model. These pressures, along with estimates of heat rejection and parasitic power requirements, are used to estimate the equipment costs. In this study no transmission line cost was considered. An installation multiplier is applied to the equipment costs to obtain the installed plant cost. This installation multiplier includes both the direct construction costs and the indirect costs, including engineering, start-up etc. The approach for estimating installed plant costs by estimating equipment costs and applying an installation multiplier was adopted from Electric Power Research Institute's Next Generation Geothermal Power Plants study (EPRI 1996).

Indirect Costs:

The different phases and activities in project development have costs such as planning and management, limited testing of exploratory wells, engineering, and other similar costs that are difficult to categorise and assign a specific value. These indirect costs are estimated as a percentage of the total cost for the activity or phase and in this study GETEM default percentages were used.

Operation and maintenance:

The operation and maintenance costs used in estimating the LCOE include:

- Labour costs
- Maintenance costs: a specified fraction of the capital costs for
  - Power plant (1.8% of capital costs)
  - Well field (1.5% of capital costs)
  - Field gathering system (1.5% of capital costs)
- With Geo-Coat equipment maintenance need is reduced hence maintenance costs fraction was estimated assuming that if we replace, for example, a pipe with Geo-coat it will not need replacement in plant lifetime and hence adjustment to the maintenance cost factors is required.
- Property taxes and insurance: based upon the total capital cost for the power plant, surface equipment, geothermal pumps, and wells that support the operation of the facility
- Royalties

3 LCOE ANALYSIS

3.1 Goal and scope

In the Geo-Coat project, various geothermal components such as pipes & casings (S1), valve stem & turbine blades (S2), turbine rotors (S3), turbine blades (S4), pump impellers (S5) and heat exchanger tubes (S6) of the geothermal power plants have been proposed for the applications of the best Geo-Geo-Coat technologies/Geo-Coat systems. It is recommended to use the best ranked Geo-Coat systems instead of SOA (state-of-the-art) materials for improved performance of these components during the lifetime of future geothermal power plant. One hypothetical Icelandic geothermal power plant, based on 303MW Hellisheiði double flash (Icelandic Perspective: IP), and one hypothetical Romanian geothermal power plant based 50kW Transgex-Oradea binary type geothermal plant (Romanian Perspective: RP) have been selected for the assessment of the economic impacts with and without adoption of Geo-Coat technology applied for pipes & well casings (S1) and turbine components (S3 and S4).

Firstly, we have explored the dimensions, length and diameters of different geothermal components such as pipes, well casings, and turbine components employed for IP and RP power plants and calculated the volume and inner surface area on the primary data provided by the consortium partners (Section 3.2). Then, we have calculated the total volume of the SOA and Geo-Coat substrate materials for different geothermal components employed in IP and RP power plants. The coating volumes for different components have been obtained using the calculated total inner surface areas and the coating thickness. Coating thickness for each component has been chosen so that the component lifetime equals the plant lifetime removing any need for replacement.

The main goal of the LCOE studies is to provide the economic performance with and without the adoption of Geo-Coat technology applied for geothermal components considering IP and RP power plants at the installation phase. The following goals should be achieved:

- Quantify and evaluate the economic impacts of the SOA materials and Geo-Coat systems (Geo-Coat substrate plus ranked coating) used for geothermal components such as pipes, turbine components and well casings.
- Compare the total economic impacts with and without the adoption of Geo-Coat systems for case studies from Icelandic and Romanian perspective.
- Use this study as a marketing tool for policymakers, stakeholders, and environmental agencies.

The intended audiences for this study are listed below:

- Geothermal pipe manufacturers
- Turbine manufacturers
- Well casing manufacturers
- Stakeholders of the geothermal plants
- Policymakers in the geothermal industry
- Consortium members
- Environmental agencies
- European Commission

In this study, we have analysed two geothermal power plants from Iceland and Romania. The scope of the study is to establish the baseline information to produce SOA and Geo-Coat systems employed for pipes, well casings and turbine rotors and blades and then to compare the economic impacts of the power plants in terms of LCOE with and without adoption of the Geo-Coat technology.

3.2 Power plant data

For the LCOE studies, the best ranked Geo-Coat systems have been considered for pipes, turbine and well casing components of IP and RP case studies. The basic data for these power plants are given in ***Table 3-a***.

Table 3-a*: Basic data of IP and RP geothermal power plants*

Plant short name	Power (MW)	Plant type	Resource temp (◦C)	Resource depth (m)	Turbines (S3-S4) (no)	Well casings (S1) (no)	Surface Pipes (S1) (km)
IP	303	Double flash	240-280	2000-3000	7	44	49.5
RP	0.05	Binary	95-110	2280-2370	1	2	2.587

The lengths and dimensions for different geothermal components of IP and RP geothermal power plants were provided by the consortium partners ON power and ICI[5] and METAV R&D[6] (given in Appendix A). To ensure data confidentiality, the length of the pipes data have been omitted from ***Table 3-b*** and ***Table 3-c***.

Table 3-b: *Data inventories for different pipe components (S1) at IP. Note that the data of pipe length, inner and outer diameter have been omitted for reasons of confidentiality. These info could be provided on a case-to-case basis upon request.*

Types of components	Length (m)	Inner diameter (mm)	Outer diameter (mm)	Material	
				SOA	**Geo-Coat**
2-phase pipes				630SS	S235JR
				630SS	S235JR
				630SS	S235JR
				630SS	S235JR
Steam pipes				630SS	S235JR
				630SS	S235JR
Brine pipes-I				630SS	S235JR
				630SS	S235JR
				630SS	S235JR
Brine pipes-II				630SS	S235JR
				630SS	S235JR

Table 3-c: *Data inventories for length of different pipe components (S1) at RP. Note that the data of pipe length, inner and outer diameter have been omitted for reasons of confidentiality. These info could be provided on a case-to-case basis upon request.*

Types of components	Length (m)	Inner diameter (mm)	Outer diameter (mm)	Material	
				SOA	Geo-Coat
Uncased pipes				630SS	S235JR
2-phase pipes				630SS	S235JR
Brine pipes				630SS	S235JR

Total volume and surface are of SOA and Geo-Coat substrate (GCS) materials consumed by different parts of the turbines employed in IP and RP plants have been calculated using the dimensions and length of rotors and blades provided by consortium partners. The data inventories for these turbine components (S3-S4) of IP and RP plants are listed in ***Table 3-d***.

Table 3-d: *Data inventories for parts of turbine components (rotors: S3 and blades: S4) of IP and RP*

Plant type and units	Turbine parts	Number of stages	Annular surface area	Materials	
			(m^2)	**SOA**	**Geo-Coat**
IP	Rotor	6	13	A470	1.2746
	Blades	6	25	Ti-6Al-4V	304L
RP	Rotor	2	1	A470	1.2746
	Blades	2	2	Ti-6Al-4V	304L

[5] Personal communication with ON and ICI partners, March 2020.

[6] Personal communication with METAV R&D partner, February 2020.

Well casing components have been used in the production wells of IP and RP plants. The total volume and surface area of the well casing components have been calculated based on the primary data provided by the consortium partners and listed in ***Table 3-e***.

Table 3-e: *Data inventories for well casing components (S1) of IP and RP. Note that the data of pipe length, inner and outer diameter have been omitted for reasons of confidentiality. These info could be provided on a case-to-case basis upon request.*

Plant type and units	Number of wells	Average length	Thickness	Outer diameter	Material	
		(m)	**(mm)**	**(mm)**	**SOA**	**Geo-Coat**
IP	44				Ti-6Al-4V	S235JR
RP	3				Ti-6Al-4V	S235JR

3.3 Materials, coatings cost and cost factors data

Based on SOA and Geo-Coat substrate material and cost data (***Table 3-f***), Geo-Coat coating data (***Table 3-g***), material cost contribution to total cost (***Table 3-h***) and equations **Eq. 3-a - Eq. 3-c**, the overall cost factors for each of the component on which Geo-Coat is applied has been calculated. The overall cost factor is multiplied by the SOA cost to come up with the Geo-Coated component cost. This approach has been used because of non-availability of data regarding component manufacturing cost distribution data.

Table 3-f*: SOA and Geo-Coat substrate material and substrate cost*

Application Area	*Substrate ID*	*Material*		*Substrate cost (€/m3)*	
		SOA	***Geo-Coat***	***SOA***	***Geo-Coat***
Casing	S1	Ti-6Al-4V	S235JR	5,600,000	2,500
Pipe	S1	630SS	S235JR	57,500	2,500
Turbine rotor	S3	A470	1.2746	343,333	283,333
Turbine Blade	S4	Ti-6Al-4V	304L	5,600,000	14,167

Table 3-g*: Cost of Geo-Coat coating, corrosion rate and substrate preparation cost*

Coating ID	Substrate preparation cost (€/m2)	Cost of 1µ thick coating (€/m2)	Corrosion rate (µ/year)
LC_HEA2	53.96	4.76	2.21

Table 3-h*: Material cost contribution to total cost*

Component	Material cost contribution in total cost	Subcomponent	Substrate	Subcomponent cost contribution in total material cost
Casing	40%	Casing	S1	100%
Pipe	40%	Pipe	S1	100%
Turbine	40%	Turbine rotor	S3	20%
		Turbine blades	S4	60%

$$\begin{aligned}
&cost\ of\ GeoCoated\ material \\
&\quad = substrate\ material\ volume * \ GeoCoat\ substrate\ rate \\
&\quad + coated\ surace\ area \\
&\quad * (substrate\ preparation\ rate \\
&\quad + coating\ thickness\ required\ for\ plant\ lifetime * coating\ rate)
\end{aligned} \quad \textbf{Eq. 3-a}$$

$$material\ cost\ factor = \frac{cost\ of\ GeoCoated\ material}{substrate\ material\ volume * SOA\ substrate\ rate} \quad \textbf{Eq. 3-b}$$

$$\begin{aligned} &overall\ cost\ factor\ for\ a\ component \\ &\quad = 1 + material\ cost\ contribution\ in\ total\ cost \\ &\quad * \sum_{subcomponent=1}^{n} \Big(subcomponent\ cost\ contribution\ in\ total\ material\ cost \\ &\quad * (-1 + material\ cost\ factor)\Big) \end{aligned} \quad \textbf{Eq. 3-c}$$

When calculating overall cost factor for a component in **Eq. 3-c** we have not considered added manufacturing cost if any for Geo-Coated material.

3.4 Icelandic Perspective (IP)

For the comparative LCOE studies, IP has been modelled after, but not exactly the same as, Hellisheiði power plant and considered to be a double flash plant. Though component dimensions from Hellisheiði have been used in this study, the substrates for the SOA components are the 'adjusted SOA substrate' from ***Table 1-b*** (column 4). This is because the Geo-Coat project focuses on material and component development for highly corrosive geothermal environments. Comparative LCOE studies has been performed with the adoption of the best ranked Geo-Coat systems (LC_HEA2_S235JR, LC_HEA2_1.2746, LC_HEA2_304L), and without adoption of Geo-Coat systems, i.e. with SOA systems (630SS, A470, Ti-6Al-4V and Ti-6Al-4V) for surface pipes, turbine rotors, blades and well casings, respectively. The pump impeller has not been considered for IP since this is not used in the Hellisheiði power plant, and the heat exchanger is not included in this study due to unavailability of data.

From data inventories of SOA and Geo-Coat systems, the total material volume, the total area of coating, and the coating thickness (area of coating times the required thickness of the coating for 30 years lifetime) for those components have been calculated based on the primary data provided by the plant operators. The total thickness of the coatings, using the best ranked coatings LC_HEA2, with corrosion rates of 2.21 µm/year, have been calculated for 30 years lifetime of the plant, giving values of about 66 µm. Using the data and formulae from Sections 3.2 and 3.3, overall cost factors for the components have been calculated and are presented in ***Table 3-i***. The overall cost factors are then used to compute LCOE for Geo-Coat coatings, which are presented in

Component	Coating	Overall cost factor
Casing	LC_HEA2	0.0060
Pipe	LC_HEA2	0.6236
Turbine	LC_HEA2	0.0103

Table 3-j.

Table 3-i*: Overall cost factor for IP*

Component	Coating	Overall cost factor
Casing	LC_HEA2	0.0060
Pipe	LC_HEA2	0.6236
Turbine	LC_HEA2	0.0103

Table 3-j*: LCOE comparison of IP*

		SOA	Geo-Coat
LCOE	***€/MWh***	**1,332.714**	**115.975**
Power Sales	***MW***	**266.21**	**266.21**
Exploration Drilling Costs (full-sized)		264,818,040.25 €	19,052,266.51 €
Small Diameter Exploration Drilling		1,989,934.18 €	1,989,934.18 €
Non-Drilling Exploration Costs		420,155.45 €	420,155.45 €
Permitting & Leasing Costs		480,317.53 €	480,317.53 €

Other Indirect Costs		13,937,791.59 €	1,002,750.87 €
TOTAL EXPLORATION COST		***281,646,239.00 €***	***281,646,239.00 €***
Well Count			
Number Production Wells Required		30.00	30.00
Number Injection Wells Required		11.32	11.32
Number of Wells Drilled to Complete Field		52.43	52.43
Well Cost			
Production Well Cost		55,170,425 €	3,969,222 €
Injection Well Cost		55,170,425 €	3,969,222 €
Drilling Cost			
Production Capacity Drilled before PPA		60%	60%
Permitting Costs		916,280 €	916,280 €
Production Well Costs		2,059,695,869 €	148,184,295 €
Injection Well Costs		832,990,848 €	59,929,315 €
Non-Drilling Costs		152,439,196 €	11,145,875 €
TOTAL DRILLING COST		***3,046,042,193 €***	***3,046,042,193 €***
Total Production Flow	*kg/s*	2400.00	2400.00
Flow per well	*kg/s*	80.00	80.00
Production Pumping	*MW*	0.00	0.00
Total Injection Flow	*kg/s*	1946.57	1946.57
Injection Pumping	*MW*	12.56	12.56
Wells Used for Injection		24.43	24.43
Surface Equipment Costs		1,083,536,471 €	675,675,933 €
Total Production Pump Costs		0 €	0 €
Total Injection Pump Costs		4,705,429 €	4,705,429 €
Indirect Costs		148,396,623 €	92,779,277 €
TOTAL FIELD GATHERING SYSTEM COST		***1,236,638,523 €***	***1,236,638,523 €***
Estimated Generator Nameplate	*MW*	290.61	290.61
Power Plant Net Output	*MW*	278.76	278.76
Geothermal Pumping Power	*MW*	12.56	12.56
Power Plant Cost (per net MW)	*€/MW*	50,960,823 €	1,075,145 €
Power Plant Cost		14,206,070,407 €	299,712,288 €
TOTAL POWER PLANT COST		***14,206,070,407 €***	***14,206,070,407 €***
TOTAL CAPITAL COST (w/o Contingency)		***18,770,397,362 €***	***18,770,397,362 €***
TOTAL CAPITAL COST (with Contingency)		**21,112,331,253 €**	**21,112,331,253 €**
Facility Staff		44.9	44.9
Labour Cost	*per yr*	3,499,477 €	3,499,477 €
Plant Maintenance	*per yr*	256,224,984 €	53,987,338 €
Field Maintenance	*per yr*	63,118,528 €	1,809,480 €
Geothermal Pump Maintenance	*per yr*	0 €	0 €
Taxes & Insurance	*per yr*	154,601,662 €	10,085,606 €
TOTAL ANNUAL O&M COST		**477,444,651 €**	**69,381,902 €**

The adoption of the best ranked Geo-Coat technology as an alternative to SOA materials for highly corrosive geothermal environments in IP demonstrates a significant saving in LCOE (from 1,338€/MWh to 116€/MWh).

3.5 Romanian Perspective (RP)

For the comparative LCOE studies, RP has been modelled after, but not exactly the same as, TRANSGEX-Oradea power plant and considered to be a binary plant. Though component dimensions from TRANSGEX-Oradea has been used in this study, the substrates for the SOA components are the 'adjusted SOA substrate' from ***Table 1-b*** (column 4). This is because the Geo-Coat project focuses on material and component development for highly corrosive geothermal environments. Comparative LCOE studies has been performed with adoption of the best ranked Geo-Coat systems (LC_HEA2_S235JR), and without adoption of Geo-Coat systems i.e. with SOA systems (630SS and Ti-6Al-4V) for surface pipes and well casings, respectively. Turbine rotors and blades are not included in this study as in binary power plant they do not encounter aggressive geofluid and hence Geo-Coat technologies are not necessary. Pump impellers and heat exchangers are not included in this study due to the unavailability of data.

From data inventories of SOA and Geo-Coat systems, the total material volume, the total area of coating, and the coating thickness (area of coating times the required thickness of the coating for 20 years lifetime) for those components have been calculated based on the primary data provided by the plant operators. The total thickness of the coatings, using the best ranked coatings LC_HEA2, with corrosion rates of 2.21 µm/year, have been calculated for 20 years lifetime of the plant, giving values of about 44 µm, respectively. Using the data and formulae from Sections 3.2 and 3.3, overall cost factors for the components have been calculated and are presented in ***Table 3-k***. The overall cost factors are then used to compute LCOE for Geo-Coat coatings and is presented in ***Table 3-l***.

***Table 3-k**: Overall cost factor for RP*

Component	Coating	Overall cost factor
Casing	LC_HEA2	0.0054
Pipe	LC_HEA2	0.5215

***Table 3-l**: LCOE comparison of RP*

		SOA	Geo-Coat
LCOE	***€/MWh***	**3,519.804**	**2,609.545**
Power Sales	***MW***	**11.28**	**11.28**
Exploration Drilling Costs (full-sized)		355,897,957.11 €	21,063,068.96 €
Small Diameter Exploration Drilling		1,989,934.18 €	1,989,934.18 €
Non-Drilling Exploration Costs		420,155.45 €	420,155.45 €
Permitting & Leasing Costs		193,198.48 €	193,198.48 €
Other Indirect Costs		18,731,471.43 €	1,108,582.58 €
TOTAL EXPLORATION COST		***377,232,716.65 €***	***377,232,716.65 €***
<u>Well Count</u>			
Number Production Wells Required		2.00	2.00
Number Injection Wells Required		1.35	1.35
Number of Wells Drilled to Complete Field		1.79	1.79
<u>Well Cost</u>			
Production Well Cost		74,145,408 €	4,388,139 €
Injection Well Cost		74,145,408 €	4,388,139 €
<u>Drilling Cost</u>			
Production Capacity Drilled before PPA		60%	60%
Permitting Costs		916,280 €	916,280 €
Production Well Costs		0 €	0 €
Injection Well Costs		132,984,030 €	7,870,379 €
Non-Drilling Costs		7,191,686 €	606,757 €
TOTAL DRILLING COST		***141,091,997 €***	***141,091,997 €***
Total Production Flow	*kg/s*	220.00	220.00
Flow per well	*kg/s*	110.00	110.00
Production Pumping	*MW*	0.89	0.89
Total Injection Flow	*kg/s*	220.00	220.00
Injection Pumping	*MW*	1.18	1.18
Wells Used for Injection		1.79	1.79
Surface Equipment Costs		8,644,579 €	4,507,753 €
Total Production Pump Costs		500,133 €	500,133 €
Total Injection Pump Costs		473,231 €	473,231 €

Indirect Costs		1,311,538 €	747,425 €
TOTAL FIELD GATHERING SYSTEM COST		***10,929,481 €***	***10,929,481 €***
Estimated Generator Nameplate	*MW*	23.17	23.17
Power Plant Net Output	*MW*	13.35	13.35
Geothermal Pumping Power	*MW*	2.07	2.07
Power Plant Cost (per net MW)	*€/MW*	99,558,336 €	99,558,336 €
Power Plant Cost		1,328,906,652 €	1,328,906,652 €
TOTAL POWER PLANT COST		***2,739,771,564 €***	***1,328,906,652 €***
TOTAL CAPITAL COST (w/o Contingency)		***3,269,025,758 €***	***1,858,160,847 €***
TOTAL CAPITAL COST (with Contingency)		**3,686,047,324 €**	**2,063,552,676 €**
Facility Staff		7.9	7.9
Labour Cost	*per yr*	605,667 €	605,667 €
Plant Maintenance	*per yr*	23,920,320 €	23,721,933 €
Field Maintenance	*per yr*	4,355,890 €	6,034 €
Geothermal Pump Maintenance	*per yr*	165,709 €	165,709 €
Taxes & Insurance	*per yr*	13,876,772 €	11,647,109 €
TOTAL ANNUAL O&M COST		**42,924,358 €**	**36,146,452 €**

The adoption of the best ranked Geo-Coat technology as an alternative to SOA materials for highly corrosive geothermal environments in RP demonstrated a significant savings in LCOE (from 3,520 €/MWh to 2,610 €/MWh).

3.6 Discussions

To evaluate economic performance of Geo-Coat technologies, LCOE analysis for two case studies (IP, RP) based upon, but not exactly the same as, Icelandic and Romanian geothermal power plants was performed. The best ranked Geo-Coat systems per application area were used in this study. In comparative LCOE studies, the best ranked Geo-Coat systems for different application areas such as well casing (S1), surface pipes (S1) and turbine components (S3-S4) have been adopted for IP and RP instead of SOA systems for those components usually employed. The results of this study are summarised in ***Table 3-m*** and ***Table 3-n***.

***Table 3-m**: Summary of cost factors*

Component	Coating	IP cost factor	RP cost factor
Casing	LC_HEA2	0.0060	0.0054
Pipe	LC_HEA2	0.6236	0.5215
Turbine	LC_HEA2	0.0103	na

Cost factor is multiplied by the SOA product cost to estimate Geo-Coated components cost i.e. a cost factor of less than one will reduce component cost and reduce LCOE. The best ranked coatings, LC_HEA2, show a cost factor of less than one for all components i.e. the best ranked Geo-Coat technologies cost less that SOA materials.

***Table 3-n**: Summary of LCOE studies*

Perspective	LCOE (€/MWh)		LCOE reduction
	SOA	Geo-Coat	
IP	1,332.714	115.975	91.30%
RP	3,519.804	2,609.545	25.99%

The study shows that the best ranked coatings (LC_HEA2) offer the best cost in terms of economic performance and reduce LCOE for the studies. The study also shows that the benefits from Geo-Coat is higher for larger plant size.

4 CONCLUSIONS

Geo-Coat technologies are being developed and designed to protect different parts and components in the geothermal power plant, particularly from corrosion, erosion and scaling effects. Geo-Coat technology can be applied to steam turbines, surface pipes, pump impellers, and well casings to extend their lifetime and reliability. Geo-Coat technology will enhance the growth of geothermal energy as it will enable exploitation of corrosive and aggressive geofluid to generate electricity - while significantly reducing the environmental impacts.

For comparative LCOE studies, the best ranked Geo-Coat systems for different application areas such as surface pipes (S1), turbine components (S3-S4) and well casings (S1) have been adopted for Icelandic and Romanian studies which are based on, but not exactly the same as, the 303MW Hellisheiði power plant and the 50kW TRANSGEX-Oradea power plant respectively. Based on GETEM and GEOPHIRES LCOE calculators we have developed the Geo-Coat LCOE calculator, which was used in this study to perform LCOE estimation with and without adoption of Geo-Coat systems for different geothermal components. The study shows an LCOE reduction of 25.86-91.30% for the best ranked coatings. All Geo-Coat material, coating, surface preparation and coating application costs use in this study are laboratory-scale costs, which are not representative costs for large scale production. We expect further reduction in LCOE for large-scale production.

This study assumes that a coating will be applied for the plant lifetime for all casing, pipes and turbine rotor & blades. This can be optimised if corrosion rates of different sections of these components is known, allowing for optimised coating application which will further reduce costs and LCOE.

This study reveals that adoption of the best ranked Geo-Coat systems for geothermal components will reduce costs for those geothermal plants operating with highly corrosive geofluid. Application of Geo-Coat technologies will also make geothermal prospects with highly corrosive geofluid commercially viable.

Appendix A – Data sheets of Icelandic and Romanian power plants provided by ON Power, ICI and METAV R&D

Table A1 - A data sheet for 303 MW Hellisheidi double flash power plant provided by ON POWER & ICI

For Icelandic power plant case study of GeoCoat application, we need the following information regarding main components involved in that plant for data inventory of GeoCoat deliverables D9.1& D9.2:

Icelandic double flash power plant

Name of the plant: Hellisheidi power plant

Power plant capacity: 303.3 MW (Units 1-6 and a low pressure Unit 11)

System	Component	Part	Quantity/comments	ID	Surface area - Inner	Surface area - outer	Total length	Length	Inner Diameter	Outer Diameter	Thickness	Material type	Material grade
					(m2)	(m2)	[redacted]	(m)	(mm)	(mm)	(mm)		
Fluid gathering	Well Pipes	Casings	44 production wells	API 9 5/8"	8668	9612	[redacted]	13-14 (unit length)	221	244.5	12	Carbon steel	K-55
				API 13 3/8"	29035	31712	[redacted]	13-14 (unit length)	315	339.8	12.2	Carbon steel	K-55
	Downhole pumps	Impeller	not used	n/a	n/a		[redacted]	n/a	n/a	n/a	n/a	n/a	n/a
Fluid transmission	Pipes	2-phase pipes		DN250	1239	1286	[redacted]	1500	263	273	5	Carbon steel	S235JR
				DN500	5432	5586	[redacted]	3500	494	508	6-8	Carbon steel	S235JR
				DN700	18099	18986	[redacted]	8500	689	711	10-12	Carbon steel	S235JR
				DN1000	18737	19151	[redacted]	6000	994	1016	10-12	Carbon steel	S235JR
		Steam pipes		DN1000	40596	41494	[redacted]	13000	994	1016	10-12	Carbon steel	S235JR
				DN1400	4486	4580	[redacted]	1000	1428	1462	17	Carbon steel	S235JR
	Turbines	Diaphragm	6 stages (units 1 and 2)			44	[redacted]			700-1300/1900-2900	50-220		
		Rotor	6 stages (units 1 and 2)			13	[redacted]			600-1300	70-160	Low alloy steel	CrMoV steel
		Rotor blades	general				[redacted]					stainless steel	
			unit 1 and 2			*25*	[redacted]	*0, 11-0, 35*				*stainless steel*	*17-4 PH (last stages)*
		Turbine casing	1 per unit				[redacted]					Carbon steel (HP pressure units)	
Reinjection system	Brine pipelines	Pipes		DN600	7464	7666	[redacted]		594	610	8	Carbon steel	S235JR
				DN700	15284	15636	[redacted]		695	711	8	Carbon steel	S235JR
				DN1000	4684	4788	[redacted]		994	1016	10-12	Carbon steel	S235JR
				DN500	776	798	[redacted]		494	508	*6-8*	Stainless steel	316L
				DN1000	9368	9575	[redacted]		994	1016	*10-12*	Stainless steel	316L

Table A2 - A data sheet for 50 kW Transgex-Oradea binary power plant provided by METAV R&D

For Romanian power plant case study of GeoCoat application, we need the following information regarding main components involved in that plant for data inver

Romanian Binary power plant

Name of the plant	TRANSGEX -Oradea	Binary pilot power plant

System	Component	Part	Quantity	API ID	Total length	Outer Diameter	Thickness	Material type
					[redacted]	(mm)	(mm)	
Brine production	Pipes	Casings	1		[redacted]	150	10	P265GH
		Casings	2		[redacted]	311	10	
		Uncased	3	API 5L	[redacted]	215	10	uncased
Brine transmission	Pipes	2-phase pipes			[redacted]	200		
					[redacted]		5	
					[redacted]			
				API 5L	[redacted]			P265GH
	Heat exchangers	Tubes			[redacted]	50	3	316
					[redacted]			
Reinjection system	Brine pipelines	Pipes			[redacted]	200	5	
				API 5L	[redacted]			P265GH

Items	Units	Values	Components	Quantities
Reservoir depth	km	2280-2370	Number of production wells	2
Reservoir / Geofluid temperature	deg C	95-110	Number of reinjection wells	1
Geofluid outlet temperature	deg C	90	Evaporators	1
Conversion efficiency	%	38	Preheaters	0
Installed power capacity	MW	0.05	Turbines	1
Full load hours annually	h	7 920	Generators	1
Specific heat capacity of geofluid	kJ /kg K	1,035	Condensers	1
Lifetime	years	20	Downhole pumps	2
Geofluid flow rate	m3 h-1	75	Feed pumps	2
Specific auxiliary power need for downhole pump relating to fluid rate	kW / m3 h-1	160	Cooling tower	1

Appendix B – python source for overall cost factor calculation

```
import json, math, re
from cloudant import couchdb
import numpy as np

COATING_IDs = ['HVOF_CA2', 'LC_HEA2']
DB = 'lcoe'
DB_URL = 'http://192.168.1.8:5984'
DB_USER = 'lcoe'
DB_PASSWORD = 'lcoe'

def substrate_rate(substrate_id, subs_type):
    with couchdb(DB_USER, DB_PASSWORD, url=DB_URL) as client:
        db = client[DB]
        substrate = db['substrate']
        substrate_rates = db['substrate_rate']['rates']
    substrate_material = [x['material'] for x in substrate[subs_type] if x['substrate_id']==substrate_id][0]
    return [x['value'] for x in substrate_rates if x['material']==substrate_material][0]

def soa_substrate_cost(substrate_material, substrate_volume):
    with couchdb(DB_USER, DB_PASSWORD, url=DB_URL) as client:
        db = client[DB]
        substrate_rates = db['substrate_rate']['rates']
    soa_substrate_rate = [x['value'] for x in substrate_rates if x['material']==substrate_material][0]
    return substrate_volume * soa_substrate_rate

def pipe_costs(pipe, coating_id, other_scenario_data):
    SUBSTRATE_ID = 'S1'
    with couchdb(DB_USER, DB_PASSWORD, url=DB_URL) as client:
        db = client[DB]
        substrate_preparation_rates = db['substrate_preparation_rate']['rates']
        corrosion_rates = db['corrosion_rate']
        coating_rates = db['coating_rate']['rates']
        maintenance_history = db['maintenance_history']
    outer_radius = pipe['outer_diameter']['value'] / 2 / 1000
    inner_radius = outer_radius - pipe['thickness']['value'] / 1000
    length = pipe['length']['value']
    substrate_volume = math.pi * (outer_radius**2 - inner_radius**2) * length
    inner_surface_area = 2 * math.pi * inner_radius * length
    soa_actual_cost = substrate_volume * substrate_rate(SUBSTRATE_ID, 'soa_actual')
    soa_cost = soa_substrate_cost(pipe['material'], substrate_volume)
```

```
    geocoat_substrate_rate = substrate_rate(SUBSTRATE_ID, 'geocoat')
    substrate_preparation_rate = [x['value'] for x in substrate_preparation_rates if x['coating_id']==coating_id and x['substrates']==SUBSTRATE_ID][0]
    coating_rate = [x['value'] for x in coating_rates if x['coating_id']==coating_id and x['substrate']==SUBSTRATE_ID][0]
    req_coating_lifetime = other_scenario_data['plant_lifetime']
    req_coating_thickness = req_coating_lifetime * coating_rate
    cost_geocoat = substrate_volume * geocoat_substrate_rate + (inner_surface_area * substrate_preparation_rate + inner_surface_area * corrosion_rates[coating_id]['value'] * req_coating_thickness)
    return soa_actual_cost, soa_cost, cost_geocoat

def pipe_factor(pipes, coating_id, other_scenario_data):
    cost_soa_actual = 0
    cost_soa = 0
    cost_geocoat = 0
    for pipe in pipes:
        x, y, z = pipe_costs(pipe, coating_id, other_scenario_data)
        cost_soa_actual += x
        cost_soa += y
        cost_geocoat += z
    return cost_soa / cost_soa_actual, cost_geocoat / cost_soa_actual

def avg_pipe_length(db, plant_code, other_scenario_data):
    if plant_code:
        pipes = db[plant_code]['pipes']
    else:
        pipes = other_scenario_data['pipes']
    lengths = [x['length']['value'] for x in pipes ]
    return np.mean(lengths)

def casing_costs(casing, coating_id, other_scenario_data):
    SUBSTRATE_ID = 'S1'
    with couchdb(DB_USER, DB_PASSWORD, url=DB_URL) as client:
        db = client[DB]
        substrate_preparation_rates = db['substrate_preparation_rate']['rates']
        corrosion_rates = db['corrosion_rate']
        coating_rates = db['coating_rate']['rates']
        maintenance_history = db['maintenance_history']
    inner_radius = casing['inner_diameter']['value'] / 2 / 1000
    outer_radius = inner_radius + casing['thickness']['value'] / 1000
    length = casing['length']['value']
    substrate_volume = math.pi * (outer_radius**2 - inner_radius**2) * length
```

```
    inner_surface_area = 2 * math.pi * inner_radius * length
    soa_actual_cost = substrate_volume * substrate_rate(SUBSTRATE_ID, 'soa_actual') * casing['number_of_casing']
    soa_cost = soa_substrate_cost(casing['material'], substrate_volume) * casing['number_of_casing']
    geocoat_substrate_rate = substrate_rate(SUBSTRATE_ID, 'geocoat')
    substrate_preparation_rate = [x['value'] for x in substrate_preparation_rates if x['coating_id']==coating_id and
x['substrates']==SUBSTRATE_ID][0]
    coating_rate = [x['value'] for x in coating_rates if x['coating_id']==coating_id and x['substrate']==SUBSTRATE_ID][0]
    req_coating_lifetime = other_scenario_data['plant_lifetime']
    req_coating_thickness = req_coating_lifetime * coating_rate
    cost_geocoat = substrate_volume * geocoat_substrate_rate + (inner_surface_area * casing['number_of_casing'] *
substrate_preparation_rate + inner_surface_area * casing['number_of_casing'] * corrosion_rates[coating_id]['value'] *
req_coating_thickness)
    return soa_actual_cost, soa_cost, cost_geocoat

def casing_factor(casings, coating_id, other_scenario_data):
    cost_soa_actual = 0
    cost_soa = 0
    cost_geocoat = 0
    for casing in casings:
        x,  y, z = casing_costs(casing, coating_id, other_scenario_data)
        cost_soa_actual += x
        cost_soa += y
        cost_geocoat += z
    return cost_soa / cost_soa_actual, cost_geocoat / cost_soa_actual

def avg_casing_length(db, plant_code, other_scenario_data):
    if plant_code:
        casings = db[plant_code]['casings']
    else:
        casings = other_scenario_data['casings']
    lengths = [[x['length']['value']] * int(x['number_of_casing']) for x in casings ]
    lengths = [item for sublist in lengths for item in sublist]
    return np.mean(lengths)

def rotor_costs(rotor, coating_id, other_scenario_data):
    SUBSTRATE_ID = 'S3'
    with couchdb(DB_USER, DB_PASSWORD, url=DB_URL) as client:
        db = client[DB]
        substrate_preparation_rates = db['substrate_preparation_rate']['rates']
        corrosion_rates = db['corrosion_rate']
        coating_rates = db['coating_rate']['rates']
        maintenance_history = db['maintenance_history']
```

```
    substrate_volume = rotor['annular_surface_area']['value'] * (rotor['thickness']['value'] / 1000) * rotor['no_of_turbine'] * rotor['no_of_stage']
    soa_actual_cost = substrate_volume * substrate_rate(SUBSTRATE_ID, 'soa_actual')
    soa_cost = soa_substrate_cost(rotor['material'], substrate_volume)
    geocoat_substrate_rate = substrate_rate(SUBSTRATE_ID, 'geocoat')
    substrate_preparation_rate = [x['value'] for x in substrate_preparation_rates if x['coating_id']==coating_id and x['substrates']==SUBSTRATE_ID][0]
    coating_rate = [x['value'] for x in coating_rates if x['coating_id']==coating_id and x['substrate']==SUBSTRATE_ID][0]
    req_coating_lifetime = other_scenario_data['plant_lifetime']
    req_coating_thickness = req_coating_lifetime * coating_rate
    cost_geocoat = substrate_volume * geocoat_substrate_rate + (rotor['annular_surface_area']['value'] * substrate_preparation_rate + rotor['annular_surface_area']['value'] * corrosion_rates[coating_id]['value'] * req_coating_thickness)
    return soa_actual_cost, soa_cost, cost_geocoat


def turbine_rotor_factor(rotors, coating_id, other_scenario_data):
    cost_soa_actual = 0
    cost_soa = 0
    cost_geocoat = 0
    for rotor in rotors:
        x, y, z = rotor_costs(rotor, coating_id, other_scenario_data)
        cost_soa_actual += x
        cost_soa += y
        cost_geocoat += z
    return cost_soa / cost_soa_actual, cost_geocoat / cost_soa_actual


def blade_costs(blade, coating_id, other_scenario_data):
    SUBSTRATE_ID = 'S4'
    with couchdb(DB_USER, DB_PASSWORD, url=DB_URL) as client:
        db = client[DB]
        substrate_preparation_rates = db['substrate_preparation_rate']['rates']
        corrosion_rates = db['corrosion_rate']
        coating_rates = db['coating_rate']['rates']
        maintenance_history = db['maintenance_history']
    substrate_volume = blade['annular_surface_area']['value'] * (blade['length']['value']) * blade['no_of_turbine'] * blade['no_of_stage']
    soa_actual_cost = substrate_volume * substrate_rate(SUBSTRATE_ID, 'soa_actual')
    soa_cost = soa_substrate_cost(blade['material'], substrate_volume)
    geocoat_substrate_rate = substrate_rate(SUBSTRATE_ID, 'geocoat')
    substrate_preparation_rate = [x['value'] for x in substrate_preparation_rates if x['coating_id']==coating_id and x['substrates']==SUBSTRATE_ID][0]
    coating_rate = [x['value'] for x in coating_rates if x['coating_id']==coating_id and x['substrate']==SUBSTRATE_ID][0]
```

```
    req_coating_lifetime = other_scenario_data['plant_lifetime']
    req_coating_thickness = req_coating_lifetime * coating_rate
    cost_geocoat = substrate_volume * geocoat_substrate_rate + (blade['annular_surface_area']['value'] *
substrate_preparation_rate + blade['annular_surface_area']['value'] * corrosion_rates[coating_id]['value'] *
req_coating_thickness)
    return soa_actual_cost, soa_cost, cost_geocoat


def turbine_blade_factor(blades, coating_id, other_scenario_data):
    cost_soa_actual = 0
    cost_soa = 0
    cost_geocoat = 0
    for blade in blades:
        x, y, z = blade_costs(blade, coating_id, other_scenario_data)
        cost_soa_actual += x
        cost_soa += y
        cost_geocoat += z
    return cost_soa / cost_soa_actual, cost_geocoat / cost_soa_actual


def hex_tube_costs(hex_tube, coating_id):
    SUBSTRATE_ID = 'S6'
    COATING_THICKNESS = 75
    with couchdb(DB_USER, DB_PASSWORD, url=DB_URL) as client:
        db = client[DB]
        substrate = db['substrate']
        substrate_rates = db['substrate_rate']['rates']
        substrate_preparation_rates = db['substrate_preparation_rate']['rates']
        corrosion_rates = db['corrosion_rate']
        coating_rates = db['coating_rate']['rates']
        maintenance_history = db['maintenance_history']
    outer_radius = hex_tube['outer_diameter']['value'] / 2 / 1000
    inner_radius = outer_radius - hex_tube['thickness']['value'] / 1000
    length = hex_tube['length']['value']
    substrate_volume = math.pi * (outer_radius**2 - inner_radius**2) * length
    inner_surface_area = 2 * math.pi * inner_radius * length
    soa_actual_cost = substrate_volume * substrate_rate(SUBSTRATE_ID, 'soa_actual')
    soa_cost = soa_substrate_cost(hex_tube['material'], substrate_volume)
    geocoat_substrate_rate = substrate_rate(SUBSTRATE_ID, 'geocoat')
    coating_rate = [x['value'] for x in coating_rates if x['substrate']==SUBSTRATE_ID][0]
    cost_geocoat = substrate_volume * geocoat_substrate_rate + (inner_surface_area * COATING_THICKNESS *
coating_rate)
    return soa_actual_cost, soa_cost, cost_geocoat
```

```
def hex_tube_factor(hex_tubes, coating_id):
    cost_soa_actual = 0
    cost_soa = 0
    cost_geocoat = 0
    for hex_tube in hex_tubes:
        x, y, z = hex_tube_costs(hex_tube, coating_id)
        cost_soa_actual += x
        cost_soa += y
        cost_geocoat += z
    return cost_soa / cost_soa_actual, cost_geocoat / cost_soa_actual


def material_factor_for_one_coating(plant_code, coating_id, other_scenario_data):
    with couchdb(DB_USER, DB_PASSWORD, url=DB_URL) as client:
        db = client[DB]
        if plant_code:
            pipes = db[plant_code]['pipes']
            casings = db[plant_code]['casings']
            rotors = db[plant_code]['turbine_rotors']
            blades = db[plant_code]['turbine_blades']
            if plant_code == 'RP':
                hex_tubes = db[plant_code]['hex_tubes']
        else:
            pipes = other_scenario_data['pipes']
            casings = other_scenario_data['casings']
            rotors = other_scenario_data['turbine_rotors']
            blades = other_scenario_data['turbine_blades']
        pipe_length = avg_pipe_length(db, plant_code, other_scenario_data)
        casing_length = avg_casing_length(db, plant_code, other_scenario_data)
    factor_soa_pipes, factor_geocoat_pipes = pipe_factor(pipes, coating_id, other_scenario_data)
    factor_soa_casings, factor_geocoat_casings = casing_factor(casings, coating_id, other_scenario_data)
    factor_soa_turbine_rotors, factor_geocoat_turbine_rotors = turbine_rotor_factor(rotors, coating_id,
other_scenario_data)
    factor_soa_turbine_blades, factor_geocoat_turbine_blades = turbine_blade_factor(blades, coating_id,
other_scenario_data)
    data = {
        "pipe": {
            "pipe": {
                'soa': factor_soa_pipes, 'geocoat': factor_geocoat_pipes, 'avg_length': pipe_length,
            }
        },
        "casing": {
```

```
            "casing": {
                'soa': factor_soa_casings, 'geocoat': factor_geocoat_casings, 'avg_length': casing_length,
            }
        },
        "turbine": {
            "rotor": {
                'soa': factor_soa_turbine_rotors, 'geocoat': factor_geocoat_turbine_rotors,
            },
            "blade": {
                'soa': factor_soa_turbine_blades, 'geocoat': factor_geocoat_turbine_blades,
            }
        }
    }
    if plant_code == 'RP':
        factor_soa_hex_tubes, factor_geocoat_hex_tubes = hex_tube_factor(hex_tubes, coating_id)
        data['heat_exchanger'] = {}
        data['heat_exchanger']['tube'] = {
            'soa': factor_soa_hex_tubes, 'geocoat': factor_geocoat_hex_tubes,
        }
    return data

def material_factor_for_all_coatings(plant_code, other_scenario_data):
    data = {}
    for coating_id in COATING_IDs:
        data[coating_id] = material_factor_for_one_coating(plant_code, coating_id, other_scenario_data)
    return data

def overall_factor_for_one(plant_code, component, coating_id, material_factor):
    def formula(material_cost_to_total_cost, factors):
        mult = 0
        for factor in factors:
            subcomponent_cost_to_total_material_cost, material_factor = factor
            mult += subcomponent_cost_to_total_material_cost * (-1 + material_factor)
        return 1 + material_cost_to_total_cost * mult
    with couchdb(DB_USER, DB_PASSWORD, url=DB_URL) as client:
        db = client[DB]
        material_factor = material_factor[coating_id][component]
        material_contrb = db['material_cost_contribution'][component]
        material_cost_to_total_cost = material_contrb['material_cost_to_total_cost']
        data = {}
        for analysis_type in ['soa', 'geocoat']:
```

```
        l = []
        for subcomp in material_factor.keys():
            z = (material_contrb['subcomponents'][subcomp]['subcomponent_cost_to_material_cost'],
material_factor[subcomp][analysis_type])
            l.append(z)
        data[analysis_type] = formula(material_cost_to_total_cost, l)
    return data


def overall_factors_for_all(plant_code, material_factor):
  data = {}
  for coating_id in COATING_IDs:
    data[coating_id] = {}
    data[coating_id]['pipe'] = overall_factor_for_one(plant_code, 'pipe', coating_id, material_factor)
    data[coating_id]['casing'] = overall_factor_for_one(plant_code, 'casing', coating_id, material_factor)
    data[coating_id]['turbine'] = overall_factor_for_one(plant_code, 'turbine', coating_id, material_factor)
    if plant_code == 'RP':
      data[coating_id]['heat_exchanger'] = overall_factor_for_one(plant_code, 'heat_exchanger', coating_id,
material_factor)
  return data
```