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D1.7 GeoHex opportunities in geothermal sector

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1 EXECUTIVE SUMMARY

GeoHex is aiming to develop high-performance heat exchanger (HX) materials for geothermal applications. The excellence of GeoHex lies in the concept of developing HX materials addressing both the improvements in the anti-scaling and anti-corrosion properties, as well as the heat transfer performance of the HX material, leading to smaller, more efficient and cheaper systems. GeoHex will use Ni-P/Ni-P-PTFE duplex and amorphous metal glass coatings to provide anti-scaling and anti-corrosion properties to a low-cost carbon steel substrate. To enhance the single-phase heat transfer performance, a nanoporous coating will be used. Also, by controlling the surface chemistry and texture, phase change heat transfer (i.e. boiling and condensation) performance will be enhanced. GeoHex technology can significantly reduce the cost of geothermal Organic Rankin Cycle (ORC) based plant.

This report describes GeoHex opportunities in geothermal sectors and beyond the formalised GeoHex opportunities by reviewing the deliverables D1.1 to D1.5 in work package 1 (WP1).

GeoHex has opportunities in geothermal power plants such as ORC based binary cycle power plants, Enhanced Geothermal Systems (EGSs), combined power plants (flash steam and binary cascade), and brine heat to district heating and in the desalination plants.

We have done an extensive literature review regarding the opportunities for GeoHex concepts beyond the geothermal energy sector, and there are many industries that use HXs for different purposes; however, there is also a lack of research for many industries about HX performance, and most research is based on water as the working fluid. Our literature review showed that there are industries beyond geothermal sectors such as the dairy industry, the petrochemical industry and oil refineries, ocean thermal energy conversion (OTEC) systems, desalination plants, the waste heat recovery sector, and industrial wastewater treatment plants, where GeoHex concepts to improve scaling and corrosions effects as well as heat transfer, can be applied.

Through the review of the deliverables (D1.1. to D1.5), we concluded that GeoHex opportunities regarding the improvement of corrosion and scaling, and enhancement of heat transfer by developing coating materials for the HXs used in the geothermal sectors and beyond can be maintained throughout the project, mitigating the identified risks, considering the recommendations made in the various deliverables (D1.1 to D1.5).

2 OBJECTIVES MET

This deliverable reports on the formalisation of the GeoHex opportunities within and beyond the geothermal energy sector. It therefore contributes to the following work package objective:

- To identify the opportunities of GeoHex in the geothermal sector and map GeoHex project activities.

3 INTRODUCTION

3.1 Overview

Geothermal energy has a potential for several applications, including power generation, geo-exchange, and direct thermal application. Geothermal energy is renewable and has low carbon impact; hence its increased use will lead to reduced use of fossil fuels in power generation and mitigate against global warming since most of the global contribution to greenhouse gases emissions come from power stations which are currently dominated by fossil fuels like coal, natural gas and diesel power plants which are polluting and non-renewable.

Geothermal energy has the potential to provide a significant part of the world's energy needs in the form of low carbon renewable energy, and therefore, this sector has a higher potential to meet the EU decarbonisation policy objectives and climate mitigation target.

However, development of geothermal power plants is expensive and takes a very long time to realise. There is a need to accelerate geothermal electricity development from the current 3-4% (Jeremiah and Kabeyi, 2019) annual growth in several regions and countries with underdeveloped or unexploited geothermal resources such as South America, Africa including Ethiopia and Tanzania, Russia in the Kamchatka peninsula, and several areas in China.

Therefore, there is a need to identify the problems and develop solutions to enable faster geothermal electricity development, reduce costs, and accelerate growth and efficiency.

The project GeoHex identified several factors affecting the growth of geothermal energy and provides solutions by improving the performance of the heat exchangers (HXs) used in Organic Rankin Cycle (ORC) based power plants.

The main types of geothermal power plants are dry steam plants, single or double flash plants, binary cycle plants (ORC based), combined plants, binary (ORC based), and flash cascade.

Since GeoHex will provide opportunities for improvements of HXs, ORC based binary plants and a common type of HX are briefly described below.

3.2 Binary cycle power plant and heat exchangers

ORC based Binary cycle power plants operate on the lower temperature of the geofluids or brine: 74° to 177°C.

Binary ORC plants use a heat exchanger to exploit geothermal fluid to heat up and vaporise a secondary organic fluid with a low boiling point that drives a turbine and produces electric power. In this way, the geothermal fluid remains within a closed loop of piping (from the reservoir to reinjection) without passing through the turbine, with no harmful emissions into the atmosphere; the working fluid also confined to separate closed loops.

Because these lower-temperature brines are much more plentiful than high temperature brines, binary cycle systems are expected to be a dominant future power plant.

The main components of a basic geothermal binary cycle power plant are the heat exchangers, preheater, evaporator, turbine, and condenser. The schematic diagram in Figure 1 shows the main components of the cycle. The basic thermodynamic process of binary cycles is the Rankine cycle, where the vapour reaches a dry saturated condition in the evaporator and is condensed in the condenser.

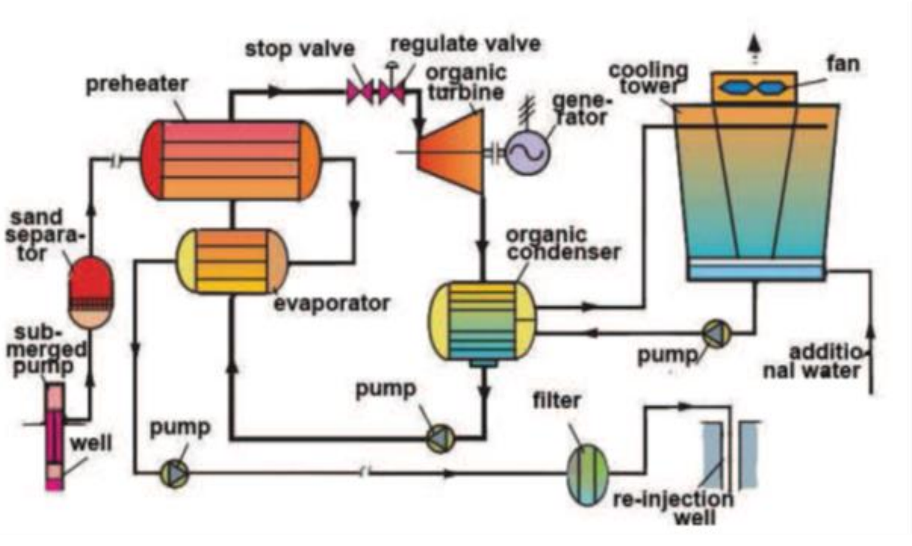

Figure 1: Geothermal basic binary cycle

The main components in the binary cycle are the HXs. Heat exchangers are devices that are used to transfer heat between two or more fluids. The fluids are usually separated by solid walls to prevent mixing or they may be in direct contact.

The two main types of HXs are shell and tube (shown in Figure 2), and plate-type. The most commonly used heat exchanger in industry is the shell and tube heat exchanger. It contains a large number of pipes packed inside a cylindrical shell. The axes of shell and pipe are parallel.

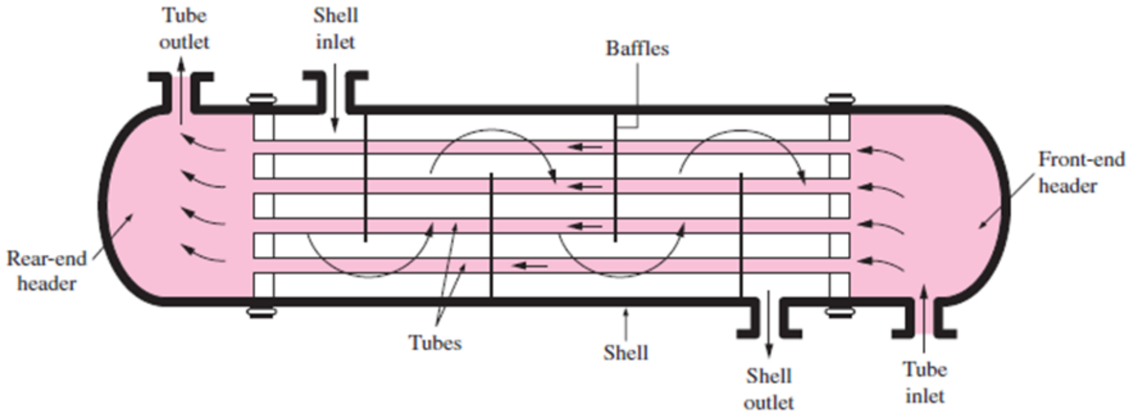

Figure 2: Schematic of shell and tube heat exchanger with one shell pass and one tube pass

3.3 Structure of report

In this report we briefly explain the GeoHex opportunities in the geothermal sectors and formalised the GeoHex opportunities, reviewing the deliverables D1.1 to D1.5. The report also describes GeoHex opportunities beyond geothermal energy sectors.

Section 4 describes the geothermal energy current issues and opportunities of GeoHex in the geothermal energy sectors.

In Section 5 we review the GeoHex deliverables D1.1, D1.2, D1.3, D1.4 and D1.5

Section 6 describes the GeoHex opportunities beyond geothermal energy.

Section 7 concludes this report.

4 CURRENT GEOHEX ISSUES AND OPPORTUNITIES IN THE GEOTHERMAL ENERGY SECTOR

4.1 Overview

Due to some of the chemical components of the geothermal fluid, the exploitation of such streams may cause scaling and corrosion in geothermal plants (Fridriksson et al.,2006).

Scaling has three main possible natures: calcite scaling, metal sulphide scaling, and silica scaling. Calcite and metal sulphide scaling usually originate at vapour/liquid separation, typically inside the production well or near the wellhead, rather than in the ORC heat exchangers. They are caused by a sudden pH change due to boiling, which leads to the dissociation of the dissolved gases (i.e. H_2CO_3 and H_2S) and precipitation of calcium carbonates ($CaCO_3$) or metal sulphides (i.e. iron, zinc, or copper sulphides). The boiling can happen inside the wells, at the hydrostatic level, or coinciding with pressure drops in the geothermal fluid (i.e. valve orifices). These kinds of scaling are thus common to all exploitation technologies of geothermal resources, both direct and binary.

Silica solubility is instead related to the temperature of the geothermal fluid; solubility decreases together with the temperature. This makes silica scaling a critical issue for binary cycles, where brine is cooled after separation. Amorphous silica and quartz (SiO_2) are formed rapidly and in large quantities when the fluid reaches the saturation point. As this phenomenon occurs while cooling the geothermal fluid, it is most likely to be formed in the heat exchanger tubes, in the reinjection lines, and in the reinjection wells.

In order to prevent silica scaling, acid additives and scale inhibitors are injected into the brine flow, and silica in suspension is crystallised by inserting crystallisers. Diluting the alkaline brine with the geothermal steam condensate, which is rich in acid components, helps reduce silica precipitations. As for metal sulphides and calcite scaling prevention, a solution consists in keeping the geothermal fluid in the liquid state at high pressure (eventually adopting pumps); in case it is not possible to maintain a liquid state, scale inhibitors are used.

Conversely, injecting acids and diluting the steam condensate may lead to metal corrosion in the various components of the system, as this is induced by fluid acidity.

Regarding the flash steam/dry steam turbine power plant, the most sensitive part affected by these phenomena in the power unit is the turbine itself. Differently from what happens in flash or dry steam turbines, for ORC binary plant, the rotating equipment is not affected by this issue, as the only parts of the binary cycle in contact with the geothermal fluid are the primary heat exchangers. Corrosion and scaling may, in fact, happen in the heat exchanger tubes and channels; the choice of materials is critical, and for the most aggressive fluids, duplex, stainless steel, and even titanium may be selected instead of the more common mild steel.

To mitigate corrosion effects, careful material selection should be performed at the design stage in order to ensure safe plant operability, minimise cost, and improve efficiency. Alkaline brine typically requires the use of mild carbon steel with a consistent corrosion allowance, while the condensing steam more likely flows in duplex steel or titanium tubes in order to avoid acid pitting.

Scaling also affects the heat transfer process; it can be considered as a thermal resistance in the heat exchange between the geothermal fluid and the metal tube, which decreases the heat exchanger efficiency during the utilisation time. Therefore, heat exchangers require regular and intensive maintenance. When the scaling resistance becomes excessive, the plant is shut down, and the heat exchanger channel covers are opened for visual inspection of the tubes, and eventually, mechanical or chemical cleaning. For this reason (easier maintenance and cleaning), shell and tube heat exchangers with geothermal fluid flowing in straight tubes are the most common heat exchanger arrangement for a geothermal ORC plant. Materials and characteristics of the heat exchangers are consequently chosen according to the specific geothermal resource.

The choice of the optimal velocity of the geofluid flow in the tubes is determined by the trade-off between scaling, erosion, and corrosion, while the selection of materials is based on the aggressiveness of the brine or steam that is obtained in the geothermal field. Increasing the liquid velocity reduces scaling but increases corrosion and erosion. On the other hand, it increases the heat transfer convective coefficient allowing for more compact and economic components, but it also increases the pressure drop along the ORC unit and the parasitic loads, as these are directly related to the square power of the velocity.

To enhance the anti-scaling and anti-corrosion properties of HX surfaces, a polymeric liner is proposed, but it can only be used at low temperatures (<150°C). When titanium (Ti), corrosion resistant alloys (CRAs), and stainless steel (SS) are used as HX material, the HX requires scaling inhibitors and frequent cleaning (through hydro-blasting). As these are high surface energy material, as time progresses, their heat transfer performance degrades (due to accumulation of scaled/corrosion product), which requires specification of oversized HXs. The thermal conductivity of PTFE based electroless duplex or amorphous metal-coated carbon steel (CS) is much higher compared with Ti, SS, and polymeric coated CS. For the phase change heat transfer case, most of the R&D activities are focused on water, and only limited research has been performed with low surface energy fluids, such as ORC working fluids. The surface energy of ORC working fluid, such as hydrocarbons (i.e. pentane, butane, etc) and refrigerants (i.e. R134a) lies within the range approximately 18 - 30 mN/m, whereas the surface energy of water is 72 mN/m. Heat transfer performance of dropwise condensation (DwC) is several times higher compared with film-wise condensation (FC), and similar results occurs for nucleate boiling (compared with film boiling).

Through the research of SOA technologies, GeoHex identified the following three factors affecting the growth of geothermal power plants:

1. **Lower overall plant efficiency**:
    - To avoid silica scaling, the brine is usually reinjected at a higher temperature; hence, the full potential of geothermal energy cannot be exploited. That causes a reduction in plant efficiency.

2. **Corrosion and scaling**:
    - To handle the aggressive geofluids, titanium or corrosion resistant alloys (CRAs) are usually recommended as heat exchanger (HX) material, which further increases the cost.
    - Scaling issues cause increased plant maintenance (cleaning) and operational (use of inhibitors) cost, and downtime.
    - In direct heat exchangers (e.g. geothermal brine to district heating) and ORC HXs, such as superheater, preheater, the evaporator is in direct contact with the geothermal brine, causing scaling and corrosion to different extents depending on the thermophysical condition and chemical composition of the geofluid.
3. **Cost**:
    - Unfortunately, very limited research activities have been done to improve the heat transfer performance of the HXs used in geothermal. Hence, poor heat transfer performance of SOA heat exchangers compels the use of HXs with larger size (to increase the heat transfer area); consequently, the capital expenditure (CAPEX) increases.
    - Various types of heat exchangers (HXs) are critical components in a geothermal power plant, especially for Organic Rankine Cycle (ORC) power generation, where the cost of different HXs can be up to ~86% of ORC total capital cost. (GeoHex Grant Agreement, 2019).

4.2 Opportunities for GeoHex in the geothermal energy sector

4.2.1 Overview

Heat exchangers (HXs) are the most critical components of a geothermal power plant, especially for Organic Rankine Cycle (ORC) based plants; the capital cost of the heat exchanger accounts for a large proportion of an ORC plant. As discussed above, because of corrosion and scaling due to geothermal brine, expensive HX materials are recommended, and degraded performance over time requires specification of over- size HXs. Hence, improvements in the anti-scaling and anti-corrosion properties, as well as heat transfer performance of the HX material, will lead to smaller, more efficient, and less costly systems.

The GeoHex project addresses the issues of improving scaling and corrosion, heat transfer and, therefore, the cost, by modifying the HX's surfaces with appropriate coatings.

The focus of the development of HXs materials is improvement in the following:

- **Heat transfer coefficient (HTC)**
- **Anti-scaling and anti-corrosion**
- **Cost**

GeoHex opportunities to improve HTC, plant efficiency and thereby the cost: It has been calculated (GeoHex Grant Agreement, 2019) that HX cost is around 86% of the total ORC cost, and this is mainly the cost of the air-cooled condenser (ACC) (~78% of the ORC cost). The high cost of the ACC is due to increased surface area requirement as the air-side heat transfer coefficient (HTC) is low (in the range of 50-100 W/m^2K), and traditional condensers are designed for film-wise condensation. As the overall HTC of the ACC is low compared with other types of condensers such as the wet cooling type, it requires a significant amount of power (parasitic load consumed by the fan motor) to drive a large amount of air to meet the cooling duty which lowers the plant efficiency. In most cases, the parasitic load reaches up to 20% of the plant output.

Therefore, the GeoHex project opportunity to improve the cost is to produce condensers with higher overall HTC through promoting sustained dropwise condensation, which will reduce the size and cost (hence reducing the plant capital cost) of the condensers, and will reduce the parasitic load, resulting in an increase of plant overall efficiency.

GeoHex opportunities for improving corrosion and scaling issues: The corrosion and scaling issues can be improved by producing carbon steel based HXs with anti-corrosion and anti-scaling properties, which will reduce the size and cost of the HXs. This will eventually reduce the plant capital cost and will enable us to extract more energy from geofluid without being affected by silica scaling.

GeoHex opportunities to improve the plant efficiency and overall heating performance: Currently, as shown in **Figure 3**, the conversion efficiency of geothermal power developments is generally lower than that of conventional thermal power plants. The conversion efficiency is significant when calculating the power potential of newly drilled geothermal wells and for resource estimation studies.

A study suggests that the power conversion efficiency from geothermal resources ranges from 10 to 17% (Barbier, 2002).

One of the significant factors beyond the thermodynamic limitation that is responsible for this low efficiency is, reinjecting brine at high temperatures to avoid silica scaling as the solubility of silica decreases with temperature.

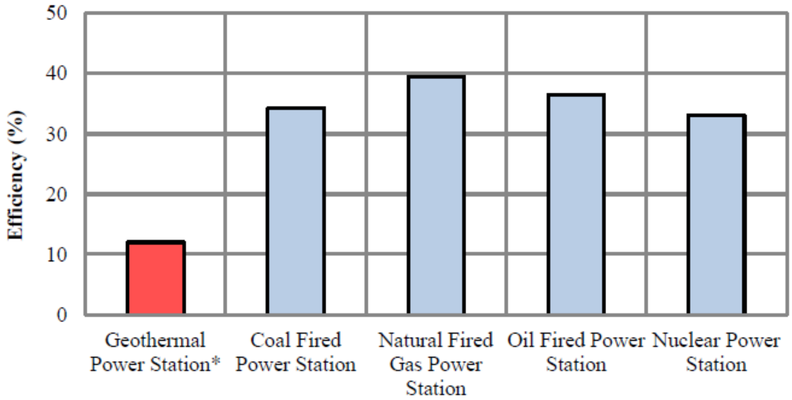

Figure 3: Efficiency comparison of different types of power station (Bertani, 2010)

A high-performance heat exchanger enabled by GeoHex, with antiscaling, antifouling, and anticorrosion properties will dramatically improve the performance of the geothermal plant by allowing a lower reinjection temperature. This will also provide options for power plant technology designers to increase the overall thermal performance of the plant.

GeoHex ideas of coatings to develop engineered surface to improve heat transfer, corrosion and scaling issues

GeoHex will develop HX materials addressing both improvements in the antiscaling and anticorrosion properties, as well as the heat transfer performance of the HX material, which will lead to smaller, more efficient, and cheaper systems.

GeoHex project will use the Ni-P/Ni-P-PTFE duplex and amorphous metal glass coating to provide antiscaling and anticorrosion properties to the low-cost carbon steel substrate. To enhance the single - phase heat transfer performance, a nanoporous coating will be used. Also, by controlling the surface chemistry and texture, phase change heat transfer (i.e. boiling and condensation) performance will be increased.

Among the different passive techniques present to enhance heat transfer performance both for single-phase and phase change heat transfer processes, surface modification seems to be the most effective. The heat transfer surface can be modified through roughening, texturing, nanostructured coating, and controlling the surface chemistry. The commonly formed structures using nanostructured coatings are nano-porous and nano-finned structures.

Boiling is a type of phase change heat transfer that occurs in the evaporator of a geothermal Organic Rankine Cycle (ORC) heat exchanger. Phase change can dramatically enhance heat transfer, compared with single-phase, as latent heat is much larger than sensible heat, while the associated large changes in specific volume can also enhance convective heat transfer (Attinger et al., 2014).

Heat Transfer Coefficient (HTC) and critical heat flux (CHF) is a measure of heat transfer. The critical factors affecting boiling heat transfer include surface morphology and roughness, microstructure, chemistry, and thermal conductivity, among others. The state-of-the-art (SOA) to enhance heat transfer coefficient (HTC) and critical heat flux (CHF) was reviewed in D1.3 and is therefore not described in the current report.

The heat transfer coefficient can be increased by transferring heat through bubbles during boiling and through droplet formation during condensation because the heat transfer performance of dropwise condensation is several times higher than conventional film-wise condensation. Nucleate boiling provides similar benefits when compared with film boiling.

DWC occurs on a surface when the surface energy of the condensing surface is low enough to inhibit the wetting of the surface by the condensing fluid. The behaviour of droplet dynamics and droplet departure frequency can strongly influence dropwise condensation efficiency. In general, plenty of parameters can change the surface characteristics and enhance the droplet dynamics and droplets' departure, such as using superhydrophobic/ superoleophobic surfaces, hydrophobic surfaces, micro- or nano-structures surfaces, gradient surfaces, hybrid surfaces and modifying surface geometry, etc to improve the droplet dynamics.

Therefore, the GeoHex approach to increase heat transfer is:

- The increased heat transfer performance will be achieved due to the promotion of nucleate boiling (for ORC working fluid) induced by the GeoHex engineered surface
- The increased heat transfer performance will be achieved due to the promotion of dropwise condensation (for ORC working fluid or steam) induced by the GeoHex engineered surface and increased frequency of droplet nucleation, coalescing, and departure.

GeoHex engineered surface for Phase Changing heat exchangers (evaporator and condenser)

Materials for condensing surface

Carbon steel, copper, and aluminium will be used to create condenser materials that will promote DWC and sucking flow condensation. A super-oleophobic, surface with metal oxide (Cuo,TiO_2, ZnO) will be synthesised on the condenser surface using a simple chemical bath composition. The use of amorphous metal will be investigated to create a superhydrophobic and super-oleophobic surface. For sucking flow condensation, copper, aluminium, and iron micro-meshes will be used. Condensing heat transfer for steam and ORC are expected to increase by 200-500% and 100-400% respectably (GeoHex Grant Agreement, 2019).

Materials for boiling surface for ORC evaporator

To create an oleophilic surface an iron doped Al-TiO_2 coating on carbon steel will be prepared by spray pyrolysis. The level of iron will determine the lipophilicity of the surface. A bi-oleophilic surface will be created by depositing an amorphous glass metal coating on a pre textured surface. The nanoporous coating will be developed by synthesising CuO by spray pyrolysis, and chemical vapour deposition (CVD) of multi-walled carbon nanotubes (MWCNT). Boiling HTC for ORC fluids is expected to increase by 80-100% (GeoHex Grant Agreement, 2019).

GeoHex engineered surface for Single Phase GeoHex Heat Exchanger (preheater, superheater)

For single-phase heat transfer cases, the increased heat transfer performance will be achieved due to an effective surface area enhancement contributed by the nanoporous coating.

For Brine side of the HXs

GeoHex considers two alternatives coatings:

- Ni-P/Ni-P-PTFE coating on Carbon steel substance synthesised by the electroless plating method.
- Amorphous metal coating by PVD synthesise.

For applications up to 250°C, the Ni-P/Ni-P-PTFE (duplex) coating is preferred, and above 250°C, the amorphous metal coating will be considered; hence, GeoHex materials can be used for all the HXs handling brine over the full temperature spectrum of current and future applications (notably EGS and the deep geothermal energy sector).

For water or ORC fluid side

To improve heat transfer, the nanoporous coating will be implemented. The nanoporous coating will be developed using a spray pyrolysis method. CVD will be implemented to form the MWCNT coating.

For recuperator

Both sides will be coated with nanoporous coating because ORC will flow in both sides of the heat exchanger.

GeoHex materials for the improvement of scaling and corrosion issues

- Ni-P/Ni-P-PTFE duplex and amorphous metal glass coating will be used on carbon steel.

PTFE will be added to the Ni-P matrix to form a composite coating. PTFE has a very high melting point and is inert in nature. It also has a low coefficient of friction. Due to low surface energy, PTFE also provides low microbial and surface adhesion. Electroless Ni-P-PTFE coating is metal-based, so it provides a high thermal conductivity, anti-abrasive property, and mechanical strength. The porosity of the Ni-P-PTFE coating is also low due to PTFE particles blocking the pores. PTFE also provides higher corrosion resistance than Ni-P coating.

GeoHex opportunities in the geothermal energy sector, as described in Sections 4.2.2 to 4.2.4, are formalised through the review of deliverables D1.1-D1.5, which are described in Section 5.

4.2.2 GeoHex opportunities in the Enhanced Geothermal System (EGS) HXs

To meet the EU target of geothermal energy penetration in the energy mix, the engineered (or enhanced) geothermal system (EGS) or deep geothermal system will receive more attention. Currently, three EGS plants are running under the demonstration phase. EGS plants are ORC based; therefore, it is important to focus on the characteristics of the relevant geofluids while developing HXs.

Enhanced Geothermal System (EGS) is a promising new technology that aims to produce clean energy by harnessing the heat beneath the earth. Domestic heating can also be provided by EGS plants along with power generation. EGS is interested in exploiting hot rock resources, where the water quantity is insufficient, and permeability is low. The permeability is enhanced by opening pre-existing fractures or creating new ones. By drilling deep enough into the earth's crust, the rocks will eventually be hot enough to boil water. Then the steam can be collected and used to run the turbine to generate electricity. A suitable drilling location must be determined based on estimates of hot rock formation below. Then, a well is drilled to access the rocks anywhere from 3-10 km below the surface. Once the desired depth is reached, cold water is injected down the well to fracture the subsurface rocks, creating a permeable channel and allowing water to circulate. This process is called stimulation. One or more production wells are drilled to access the newly created reservoir, which provides access for the hot steam. The superheated water then heats a secondary fluid, which then drives a generating turbine. Most EGS cycles are closed-loop as fluid is reused. Figure 4 shows such a basic layout of the EGS power plant.

As long as the subsurface structure is intact, an EGS plant is expected to produce electricity for decades before the temperature of the reservoir diminishes.

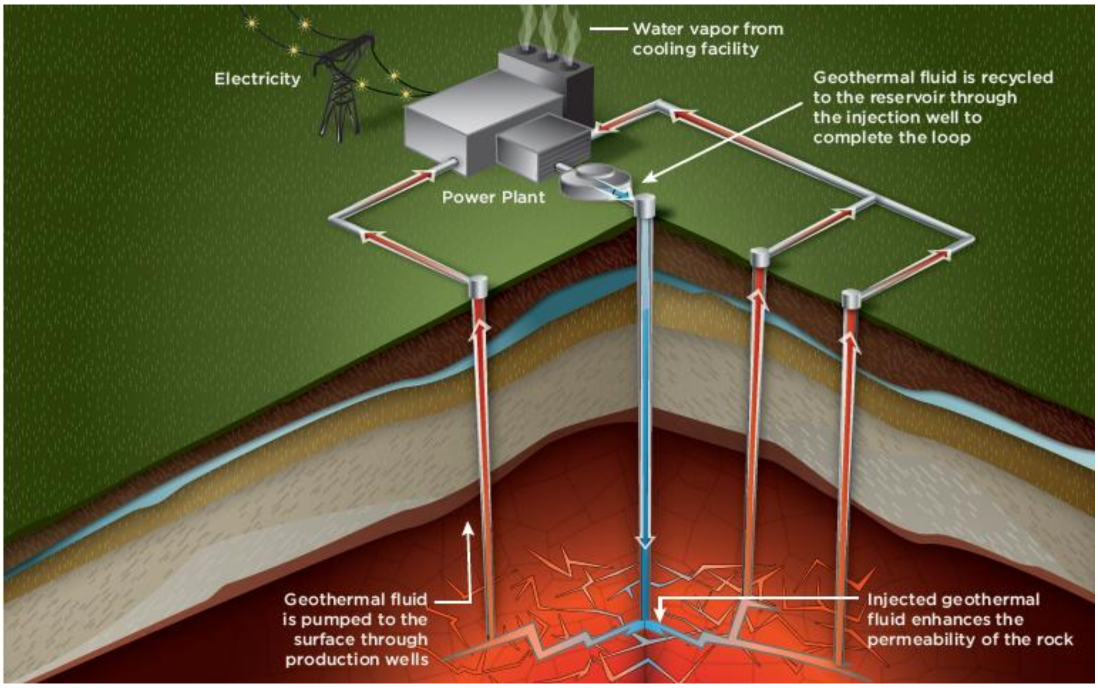

Figure 4: Layout of an EGS plant

The number of geothermal power plants based on EGS around the world is around 24. In 2010, global geothermal power capacity was around 11 GW_e, and electricity generation was 67.25 TWh_e/yr (Bertani, 2012; Chamorro et al., 2012). According to the International Energy Agency (IEA), by 2050 the total amount of power generated from geothermal energy is estimated to be 1400 TWh, which is around 3.5% of total predicted electricity to be produced that year. EGS could produce 100 GW_e of power in the USA alone by 2050 if a reasonable investment is guaranteed (Tester et al., 2006).

In the case of the European region, for depths between 3 to 10 km and temperatures above 150°C, the estimated potential is more than 6500 GW_e. 35 GW_e is the estimated potential of sustainable or renewable energy (Chamorro et al., 2013). The 1.5 MW_e plant located at Soultz-sous-Forêts, in France is currently the most advanced EGS plant.

In deep (3-10km) wells the geothermal fluid is more aggressive, and therefore silica scaling and corrosion are the major issues in EGS power plant. Scaling and corrosion reduce the efficiency of power generation and life of the reinjection well. The potential for silica scaling depends on the solubility of amorphous silica. This solubility depends on factors such as temperature, pH, and ionic strength (Chan, 1989). Acidifying, water jetting, or alkaline injection methods have been proven to solve or reduce the silica scaling formation issue. Physical separation methods, such as sedimentation and filtration, can also be considered. Due to scaling and corrosion issues, HXs are oversized by 20-30%, and therefore, the cost increases (GeoHex Grant Agreement, 2019).

The GeoHex coating can be used to improve the scaling and corrosion issues in the HXs of EGS and also can improve the heat transfer, which will reduce the cost by reducing the size of the HXs.

4.2.3 GeoHex opportunities for a basic flash plant to recover heat from brine before reinjection and transfer heat to district heating

Existing single-flash power plants can be improved by adding an ORC system on the separated brine stream, before reinjection. This makes it possible to produce more power from the same geothermal resource.

After flashing at the separator (with initial temperature 212°C), the saturated brine (165°C) leaves (state point d in **Figure 5Figure 2**) the separator. Due to silica scaling issues, in most cases (with higher salinity and pH), the brine leaving the separator cannot be used and is reinjected (red dotted line). In this situation, GeoHex enabled HXs can be used to extract a significant amount of energy from the brine before reinjection (**Figure 5**). We can produce power from the recovered energy by adding a new ORC block. The brine can be directly fed to the ORC block by fabricating relevant HXs such as preheater, evaporator, and superheater, etc based on the GeoHex material. The heat extracted by the ORC fluid can be available for district heating.

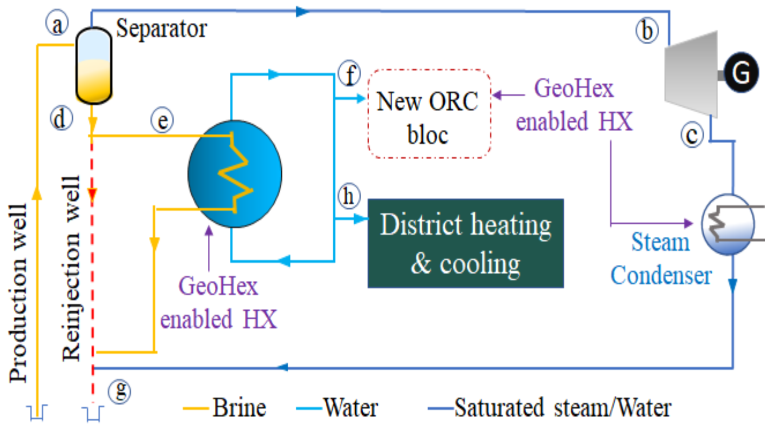

Figure 5: GeoHex creating opportunities for a basic flash plant to recover heat from brine before reinjection

4.2.4 GeoHex opportunities in water desalination using geothermal energy

Renewable energies such as wind, solar and geothermal can be incorporated in increasing water supply in water-scarce regions (Mahmoudi et al., 2009). Implementing these technologies will help to bypass the problems of rising fuel prices and decreasing fuel supplies.

When geothermal energy is used to power systems such as desalination plants, the requirement for thermal storage can be avoided. The energy output is also stable compared with wind and solar (Sablani et al., 2003).

Desalination is a multibillion-dollar, worldwide industry. As such, there have been numerous assessments of desalination technologies and costs. Multistage flash (MSF), multi-effect distillation (MED), and reverse osmosis (RO) are the top three desalination technologies in terms of worldwide installed capacity (Ziolkowska,2015). RO is an all-electric technology, whereas MSF and MED are primarily thermal, with some electricity demand for pumping and controls. RO is the leading desalination technology worldwide and is typically the lowest-cost option for seawater desalination.

For geothermal desalination designs, one could employ the geothermal source for electric power production and couple that power source with a RO system. **However, electricity generation with a low-temperature geothermal resource is very inefficient,** so direct use of the geothermal heat is preferred.

Membrane Distillation: A Good Match for Geothermal

Membrane distillation was originally proposed in the 1960s but has only recently been the subject of commercial interest because the technology to produce thermally stable membranes has improved. MD offers several potential advantages, including that it:

- Produces superior product water-quality compared with RO. High-purity product water is a general characteristic of thermal desalination technologies.
- Can treat higher-salinity brines than RO.

- Uses low-grade heat for its primary energy input (<100°C).
- Accommodates sensible (e.g. hot water) heat input.
- Operates at near-ambient pressure.
- Uses lower-cost membranes due to pressure and temperature conditions that allow the use of inexpensive plastics (e.g. PVDF or polypropylene) as construction material and a pore size that is orders-of-magnitude larger than required for RO membranes.
- Provides a modular design that is amenable to small-scale facilities, and that can tolerate variable operating conditions, including stop/start cycles.

The basic components, including a heat exchanger of an MD system, are depicted in **Figure 6**, its showed that the geofluid passing through the HX and then to an injection well. The source water is heated in the HX and the MD membrane then exploits the temperature difference to separate the product water from a more concentrated brine that is sent to a drain.

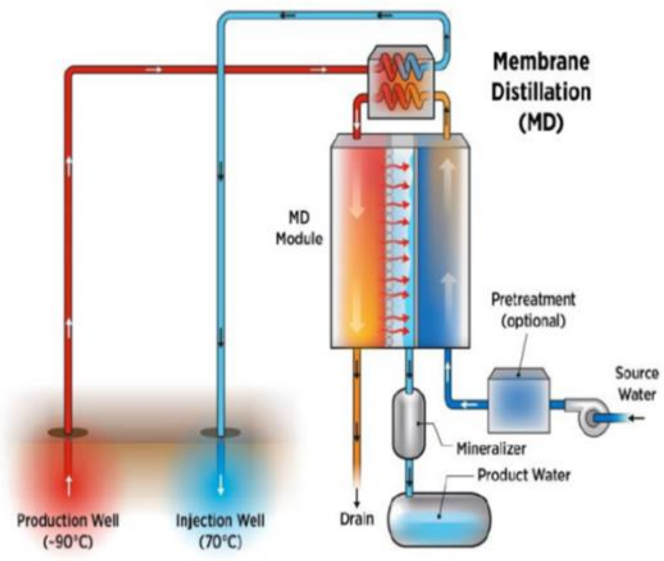

Figure 6: Basic MD system with a hot water source. Water vapour from the source water passes through the membrane from the hot-brine side to the cool-permeate side.

GeoHex opportunity: The GeoHex concepts of improving scaling, corrosion, and heat transfer, can be applied to the heat exchanger used in this basic MD desalination plant, as geothermal brine is used here as a heat source. Therefore, scaling and corrosion are significant issues and require improvement.

5 REVIEW OF THE DELIVERABLES D1.1 TO D1.5

5.1 Overview

GeoHex novel opportunities in the geothermal sector were described in Sections 4.2.2 to 4.2.4. In Section 5 we will briefly review project deliverables D1.1 to D1.5 to formalise the GeoHex opportunities in the geothermal energy sectors.

5.2 Structure of heat exchangers that will be used to demonstrate materials improvements: D1.1 – Analysis of HX technologies for geothermal and HXs structure

The purpose of this deliverable is to discuss a list of SOA geothermal power plants with a short description of the electricity production cycle, including heat exchangers technologies and operating fluid for electricity production. Based on this the report:

- Elaborated recommendations made regarding the structure of the heat exchangers that will be used to demonstrate materials improvements in the GeoHex project.
- Defined criteria to assess the most relevant HX geometries compatible with the surface enhancements.
- Recommended the ORC fluids depending on the operating temperatures.

This deliverable described the State-of-the-Art of heat exchanger (HX) technologies relevant for geothermal applications. Following the general presentation of geothermal power plants involving ORC systems and the list of worldwide binary-cycle plants, focusing on the HX main technologies and the operating conditions (working fluids, temperature, pressure, heat transfer coefficient, etc) of ORC systems. It concerns phase change HXs; the evaporator, the condensers (water-cooled or air-cooled), and the one-phase HXs (pre-heater, recuperator). A patent analysis is also provided for verification of the novelty.

The report provided some considerations/recommendations regarding the structure and the materials of the HXs that will be used to demonstrate material deposit improvements for GeoHex HXs:

- Major types of geothermal power plants are dry steam, single-flash, double-flash, and binary-cycle plants.

Regarding working fluids:

- The main working fluids at commercial scale are n-pentane, isopentane, R134a, and R245fa.
- Binary power units running on hydrocarbons are equal to approximately 83% of the total installed capacity of all the binary power units in the world.
- Relatively cheap hydrocarbons (pentane, isobutane, isopentane, etc) characterised by good thermodynamic and thermal properties are explosive and flammable and can be used in open type power plants, which is not always acceptable to areas with negative winter temperatures.
- For low and mid-range heat source temperatures (<150-200°C), the hydrofluorocarbons (HFC) R134a and R245fa are preferred.
- Simulations and thermo-economic calculations show that at low geofluid temperatures (< 200°C), using refrigerants (such as HFC) as the ORC working fluid results in slightly higher performance than hydrocarbons.

Regarding heat exchanger technologies: the most relevant heat exchangers for large-scale geothermal power plants are shell-and-tube heat exchangers. However, plate-type heat exchangers are the most cost-effective (lower heat transfer surface). Therefore, the proposed configurations for GeoHex tests are:

- For evaporator:
  - Carbon steel shell-and-tube heat exchanger.
  - Stainless steel plate-type heat exchanger. According to the operating pressure (to be defined and confirmed), welded or brazed plates will be used on the working fluid side. This would mean that no material deposit could be made on the evaporation side in the plate-type heat exchanger.
- For condensers:
  - Carbon steel shell-and-tube heat exchanger (water-cooled condenser).
  - Fin-and-tube heat exchanger (air-cooled condenser, material to be defined).
- For liquid/liquid heat exchanger:
  - Carbon steel shell-and-tube heat exchanger.
  - Stainless steel plate-type heat exchanger.

5.3 SOA of heat exchanger (HX) materials and heat exchanger failure analysis through failure mode effect analysis (FMEA): D1.2 – A Review of the SOA materials for geothermal HX and limitation.

This deliverable provides a review addressing the:

- Current state-of-the-art (SOA) materials used for heat exchangers, with a focus on HX materials used in geothermal environments.
- Expected geothermal brine compositions and the effects of brine composition, as well as specific conditions, pH, temperature etc, on materials performance.
- Specific materials used in geothermal heat exchangers,
- Failure modes that might occur in geothermal heat exchangers.
- Environmental limits for materials under various geothermal conditions
- A failure mode and effects analysis for the GeoHex heat exchanger.

This report has reviewed the SOA of materials for geothermal heat exchangers, with consideration given to the corrosivity of the particular geothermal environment. Scaling and its mitigation have also been considered as well as failure modes and their effects. The following conclusions were drawn from the review:

- SOA materials for geothermal heat exchangers include carbon steel, stainless steel, titanium alloys, copper alloys, and nickel alloys
- Silica scaling can be controlled with water treatment, and a pH, of the treated brine, of 5-6 is thought to be effective. The risk of corrosion with such a pH is thought to be minimal.
- Scaling removal via water blasting is thought to be more effective for larger heat exchanger openings.
- The cost of cleaning, for scaled heat exchangers, is thought to be higher than costs related to water treatments.
- Materials compatibility with working fluids is not a concern for heat exchangers without direct contact.
- Separator water after the second flash, at the Hellisheið planti, would not be considered to be corrosive to steels if the level of aeration was low.
- An FMEA for the GeoHex heat exchangers was conducted, and risks were generally determined to be fairly low. Mitigations were identified to further reduce risk, and these included appropriate maintenance, including water treatment and operational control, as well as considerations in design.

5.4 Identification of the characteristics of optimum surfaces for flow boiling heat transfer related to ORC working fluid: D1.3 – Ideal flow boiling surface for ORC fluid.

This report provides a review focusing on:

- SOA research and practice on the enhancement of HTC and CHF.
- A more detailed review of enhancement techniques that will be used in GeoHex.
- Discussions on the correlations between HTC and CHF and thermocouple data as well as bubble dynamics parameters, determined through image acquisition systems and modelling.
- The rationale behind imaging aspects common to both boiling and condensation (covered in D1.4, experiments).

This deliverable reviewed the characteristics of ideal boiling surfaces, for low surface tension fluids, as well as the specific processes that will be used in the GeoHex program, and correlations between experimental data and heat transfer characteristics. This review identified that the main factors that enhance passive heat transfer performance, for ideal boiling surfaces, include:

- Increased numbers of active nucleation sites using micro- or nano-sized roughness.
- Wicking to allow rewetting of the structure and to allow the fresh liquid to be delivered to the heated surface.
- Separation of vapour and liquid flow streams so that rewetting is not prevented because of vapour release. This includes sucking-evaporation mode surfaces, where evaporation causes sucking of liquid from networked inactive cavities.

It is found in this review that there is a lack of engineering knowledge available in the literature regarding the surface enhancement, such as; how the engineered surface would behave with different fluids types. It is also not clearly understood what would happen when scaled to full size. As adequate data are not available in the literature for the design of structures or to inform design parameters, it was therefore decided that the design parameters will be optimised with data obtained in the GeoHex program.

The review identified that there is a lack of data discussing the effect of process parameters on heat transfer and corrosion performance. There also appears to be a lack of long-term test data to prove the longevity of any coatings, and it was noted that most cost studies have investigated heat transfer enhancement with water as the working fluid, rather than fluids more appropriate for heat exchangers. Despite these deficiencies, the reviewed data will be useful as a starting point for the coating development in the GeoHex program, and the data generated by GeoHex will be a valuable addition to the current published literature.

5.5 Ideal surface for condensation of water and ORC working fluid in terms of surface morphology and chemistry: D1.4 – Ideal condensing surface for water and ORC fluid.

Dropwise condensation provides higher heat transfer than film-wise condensation. The formation of droplets depends strongly on the wetting ability of the liquid. The lower the wetting ability, the higher the probability of droplet formation. The amount of wetting is a key parameter in the efficiency of condensation heat transfer.

This report reviewed the underpinning science behind the wetting of solid surfaces by liquids, and approaches to the generation of the non-wetting behaviour that leads to droplet formation rather than film formation so that higher heat transfer can be assured through dropwise condensation.

This review discussed the characteristics of ideal surfaces for condensation heat transfer, with water as well as low surface energy fluids, e.g. ORC working fluids, with a specific focus on the enhancement of DWC. The effects of surface energy and texture, in relation to DWC, have also been reviewed, along with correlations between condensation heat transfer and physical parameters, e.g. droplet radius.

The review of the current state-of-the-art includes particular reference to ultralow surface tension liquids such as 1,1,1,2-tetrafluoroethane (also known as R134a), which has been identified as a candidate refrigerant in the GeoHex project.

Some important findings:

- The ideal characteristic for condensation heat transfer enhancement will be that heat transfer surfaces have a high degree of hygrophobicity. This can be achieved by:
    - Introducing roughness into the surface.
    - Understanding key design rules to determine repellent behaviour.
    - Identifying material and roughness combination that give the highest contact angle, and lowest contact angle hysteresis.
- Dual scale surface roughness increases hydrophobicity. This is the mechanism behind the superhydrophobicity of the lotus leaf. The underpinning principles behind the formation of superhydrophobic surfaces are relatively well understood, from the perspective of having a surface that is a composite of the solid and entrapped air. However, the design rules to achieve such conditions are not well understood, particularly in relation to fluids other than water.
- Ideal surfaces will have surface chemistries that minimise electrostatic interactions and formal reactions between the solid and the liquid.
- Ideal surfaces will also have topographic features that enable entrapped air to act as a structural part of the composite surface.

Correlations for condensation heat transfer have been reviewed in this deliverable, and the validity of these correlations will be tested against the data generated in the GeoHex project.

Most of the literature is focussed on the repellence of water, and discussion centres around superhydrophobicity. Other liquids of interest tend to be hydrocarbon oils and so there is a smaller, but significant corpus of work on oleophobicity. The typical surface tension of liquid hydrocarbons is <20mN/m. Very high levels of repellency to liquids with surface tension values of <10mN/m are rarely reported.

The potential of these liquids to fill textured surfaces is very high, and so most of the textures that adopt Cassie-Baxter behaviour for higher surface tension liquids will transition to Wenzel with such low surface tension liquids. There are some emerging reports, however, such as the article by Pan et al. (2018).

The key challenges facing the GeoHex project are the design and development of surface topographies on the target substrates and the modification of the surface chemistry to provide the necessary surface energy for the solid. This will lead to the promotion of dropwise condensation, leading to high heat transfer. The retention of this behaviour for the lifetime of the heat exchanger for condensing water is central to success for the steam condenser. The challenge for the dropwise condensation of R134a, which has a surface tension of 8.37mN/m, is more fundamental. Achieving super-repellence to this chemical will require far higher performance than has been reported in the literature. However, it is understood from the literature that proper structural surface management will be key to achieving this goal.

This report has been generated for making it informative for WP3, which will focus on the development of materials for organic Rankine cycle (ORC) and steam condensers that promote droplet formation as opposed to film forming of ORC working fluids such as hydrocarbons, fluorocarbon refrigerants and, of course, water.

5.6 Characterisation of ORC working fluid in terms of specific heat: D1.5 – Thermophysical characterisation of ORC working fluid.

The purpose of Deliverable 1.5 is to summarise the thermophysical properties of ORC fluids. In order to ensure the maximum utilisation of energy sources, the selection of ORC working fluid is important. This can be done by analysing the thermodynamic properties.

Some key thermophysical properties should be considered while selecting the ORC fluid.

- **Dry/Wet/Isentropic nature of working fluid**
  Dry or isentropic fluid is preferable for geothermal power since they do not require additional superheating and do not form liquid droplets inside the turbine.
- **Critical Temperature and Pressure**
  The maximum operating temperature and pressure should be less than the critical point of the working fluid.
- **Maximum operational temperature and pressure**
  There is no definite way to determine the maximum operational temperature and pressure of a cycle, but it must be less than the critical point of the working fluid. According to Rayegen and Tao, maximum pressure would be such that a maximum of 10% liquid mass is permissible inside the turbine.
- **Latent heat of vaporisation**
  The amount of energy required per unit mass to change from liquid to vapour phase. It decreases with an increase in pressure and, at the critical point, becomes zero.
- **Thermal Conductivity**
  A higher value of thermal conductivity indicates that heat transfer is easier through the fluid.
- **Surface Tension**
  According to Morgan et al. (1949), at a lower value of critical heat transfer difference, overall heat transfer coefficient increases with a decrease in surface tension.

In this deliverable, the thermophysical characterisation of most common ORC working fluids has been summarised at a reference temperature (Tr 298.15K) and reference pressure (Pr 0.1 MPa) together with sources of equations of state (EoS) available in the literature for calculations the thermophysical properties of ORC fluids as a function of temperature and pressure. A total of 43 ORC fluids for geothermal applications are listed with their thermophysical properties that can be used at low to high temperatures: 80 - 350°C related to geothermal applications. If necessary, for other ORC fluids, thermophysical properties can also be calculated using the CoolProp library a European open source thermophysical property database.

The data gathered in this report will allow the selection of appropriate ORC fluids to meet varying requirements identified within the project (WP2-WP4).

6 GEOHEX OPPORTUNITIES BEYOND GEOTHERMAL SECTOR

6.1 Overview

The primary objective of GeoHex is to develop coating materials for geothermal based heat exchangers in order to ensure higher heat transfer, reduce corrosion fouling and scaling, improve heat transfer surface so that boiling, and condensation can take place effectively, as these two-process ensured higher heat transfer. However, heat exchangers are versatile in operation. Heat exchangers play an important role in many industrial applications. They are implemented for the purpose of heating and cooling in large scale industrial process fluids.

Heat exchanger designs are considered dynamic because they can be developed for any industrial process based on temperature, pressure, type of fluid, density, chemical composition, etc.

Damage of equipment due to untreated water is a very common occurrence in heat exchanger applications. For water treatment, chemical methods are widely preferred.

In the USA, every year, 7.3 billion dollars worth of chemicals are released into the air, dumped in streams, and buried in landfills. Around 40% of these chemicals are used to control scaling issues in cooling towers, condensers, boilers, and other heat transfer equipment. 2 billion dollars worth of waste is produced, and gallons of contaminated water are disposed of due to this problem.

Maintenance methods for heat exchangers include acid cleaning, sandblasting, high-pressure water jet, bullet cleaning, and drill rods.

Purification, the addition of chemicals, or a catalytic approach are typically used to minimise fouling in HXs for large scale cooling water systems. However, most of these chemicals are hazardous to the environment.

Industrial heat exchangers

Industrial heat exchangers are thermal devices that allow the transfer of thermal energy between two or more media at different temperatures. They have many applications throughout different industries including, but not limited to:

- Power plants;
- Petroleum and oil and gas industry;
- Chemical processing plant;
- Transportation;
- Alternate fuels;
- Cryogenic;
- Air conditioning;
- Refrigeration;
- Food processing;
- Heat Recovery.

We have reviewed the literature to find the opportunities for GeoHex concepts in selected industries where heat exchangers are used and found a number of potential applications. These are discussed in Sections 6.2to 6.9. However, due to a lack of data available in the literature, some industries were not possible to include in this report, such as air conditioning, refrigeration, alternate fuel, cryogenic, etc.

6.2 Dairy industry

The dairy industry is a lucrative source for heat exchanger applications. The global dairy market is predicted to grow with a projected compound annual growth rate (CAGR) of 5% over the period of 2020-2025. In 2018, the global milk output was 843 million tons, a 2.2% increase from 2017. This increase is attributed mainly to India, Pakistan, the USA, Turkey, Argentina, and the European Union. The source of this increased demand is due to growing population, higher income, and rising health consciousness (Mordor Intelligence, 2019b)

Fouling of heat exchangers in the milk industry is a major problem with high associated costs. Considerable research has been carried out to address this problem. It reduces heat transfer efficiency and increases the pressure drop across the heat exchangers. Additionally, due to fouling, deterioration of product quality occurs since the product cannot be heated to the required temperature.

Heat exchanger fouling in the milk industry is a rapid process. This problem is more severe in the milk industry than in sectors such as petroleum and petrochemical. Whereas in these sectors cleaning the heat exchangers once or twice in a year is sufficient, in the milk industry, the exchangers require daily cleaning. This causes an interruption in production, lost productivity, energy loss, environmental impact and requires extra manpower (Gilham et al., 2000; Georgiadis and Macchietto, 2000) found that the cost due to interruption in production is higher than the cost due to a reduction in performance efficiency. It has been reported that up to 80% of the production cost in the dairy industry can be attributed to fouling and cleaning equipment (Van Asselt et al., 2005).

Factors that control the fouling in the milk industry are:

- Milk quality;
- Operating conditions;
- Type and characteristics of heat exchanger;
- Presence of microorganisms.

Fouling in the milk industry can be classified into two types (Burton, 1968; Lund and Bixby, 1975; Changani et al,1997; Visser and Jeurnink, 1997):

- Type A (protein fouling);
- Type B (mineral fouling).

It has been observed that more than 50% of fouling is protein fouling. Two major proteins are found in milk, α-lactalbumin (α -La) and β-lactalbumin (β-Lg). Dalgleish (1990) found a relationship between the denaturation of native β-Lg and the fouling of heat exchangers. But Van Asselt et al. (2005) state that β-Lg is not responsible for the fouling reaction. When milk is heated β-Lg unfolds and exposes the core, containing reactive sulfhydryl groups. The unfolded protein molecules then react with similar or other types of protein molecules such as α – La and forms aggregates (Jeurnink and de Kruif, 1993). Aggregated proteins are larger in size than denatured ones, so their transportation may be difficult (Treybal, 1981; Chen, 2000).

Delplace et al. (1994) observed that only 3.6% of denatured β-Lg was involved in deposit formation. According to Lalande and René (1988), this value was close to 5%.

Changani et al. (1997) observed the fouling occurs when aggregation takes place next to the heated surface. Toyoda et al. (1994) modelled milk fouling based on the assumption that aggregated protein is mainly responsible. Similarly, Delplace et al. (1997) stated that fouling is caused due to the aggregation reaction of protein. According to de Jong et al. (1992), the formation of protein aggregates reduces fouling. Chen (2000), Bansal and Chen (2005), and Bansal et al. (2005) showed using mathematical modeling that both denatured and aggregated proteins are responsible for fouling.

An induction period is required for the formation of protein aggregates before any noticeable amount of deposit is formed. According to de Jong (1997) this time period is from 1-60 minutes for tubular heat exchangers. Belmar-Beiny and Fryer (1993) suggest that for plate type heat exchangers, this time is shorter.

Denaturation of the native protein in heat exchangers starts at temperatures above 70-74°C (Fryer and Belmar-Beiny, 1991).

Gasketed plate heat exchangers are used mostly in the dairy industry due to high heat transfer performance, lower temperature gradient, higher turbulence, and easier maintenance than shell and tube type heat exchangers (Delplace et al., 1994). Nano coating technology can be implemented to reduce heat exchanger fouling.

The adhesion of deposits can be reduced by-

- Decreasing the surface energy of the metal.
- Coating the metal surface with high anti-adhesion material produced using nanotechnology.

Beuf et al. (2003) studied the fouling of dairy products on modified stainless steel in the Alfa Laval plate heat exchanger. The following surface modification techniques were suggested

- Coatings such as:
  - Diamond-like carbon (DLC);
  - Silica;
  - SiO_x;
  - Ni-P-PTFE;
  - Excalibur;
  - Xylan.
- Ion implants (SiF^+, MoS_2).

No significant difference was found in his research, but Ni-P-PTFE coating showed the highest cleaning efficiency.

Kananeh et al. (2010) tested using multiple coating materials and found that epoxy resin-based coating and polyurethane-based coating reduced milk fouling. PTFE coated exchangers showed higher fouling than standard stainless-steel plates. Electropolished plates were also tested, and they showed lower deposit build-up than regular stainless-steel plates, and the result was almost comparable to coated plates. Cleaning in place (CIP) time was observed for all coatings. The CIP value reduced for all the coatings, by 90% for Ni-P-PTFE, and by 36% for polished electro plate.

GeoHex opportunity: Therefore, GeoHex offers potential in this industry. By using GeoHex Ni-P-PTFE coating in the HXs, fouling can be improved which will result in a lower CIP time thus reducing cost as the downtime will be less.

6.3 Petrochemical industry and oil refinery

Tubular type heat exchangers have been popular in the petrochemical industry for many decades. But for some years, sealed and fully welded plate type exchangers have also taken a share in the market segment. The efficiency of oil refinery and petrochemical units depends on the uninterrupted operation of all equipment. In oil refineries, not only the heat exchangers but other types of equipment not related to heat transfer, such as tanks, pumps, filters, compressors, columns, ejectors, reactor trays, membranes, etc, are prone to fouling. In the petrochemical industry, heat exchangers account for about 40% of the total quality of refinery process equipment, accounting for about 20% of the investment cost of the construction plant (Yaang, 2019).

A technical report from GE Power & Water describes the economic impact of fouling and corrosion in refineries. They suggest chemical methods to improve these situations such as:

- **Dispersants**

  Dispersants limit the particle size of solids in the system. Efficacy of dispersants varies depending on the type of deposits. They prevent small particles from agglomerating to form larger particles which form deposits more easily. Additionally, they prevent small particles from attaching to already existing deposits. Maintaining high velocity helps to keep small particles from setting into process equipment. Dispersants can also act as a surface activator, which hinders a particle’s ability to lay down on the metal surface.

- **Corrosion inhibitors**

  These minimise the contact between the corrosive fluid and metal surface.

- **Metal coordinator**

  They modify the metal ions by complexing, thus reducing the catalytic activity of metal to minimise the polymerisation reactions.

- **Polymerisation inhibitors**

  Free radical polymerisation inhibitors are designed to react immediately with any radical formed in the system, which will create a new stable molecule. This will no longer contribute to propagating the reaction. They serve to reduce the polymerisation of olefins, some of the sulphur compounds, and stabilise unstable feedstock. Non-free radical polymerisation inhibitors, on the other hand, reduce the polymerisation reaction of carboxylic acids and some of the nitrogen compounds.

Chun et al. (2012) took a different approach to fight fouling and corrosion of heat exchangers in the petroleum industry. They suggested that pipes for the heat exchanger should be made from aluminium and carbon steel alloy, which shows resistance against sulfidation or sulfidic corrosion and fouling. Vibration can induce shear motion in the liquid. This reduces the formation of any foulant by reducing the viscous boundary layer adjacent to the walls of the heat transfer element. Less than 0.25μm surface roughness is suggested to prevent deposition forming. They also suggested the formation of a heat transfer surface from a silicon-containing steel composition, including an alloy and a non-metallic film formed on the surface of the alloy.

GeoHex opportunity: Therefore, GeoHex concepts using less corrosive carbon steel pipe with Ni-P-PTFE coating can be used in this industry to reduce fouling and corrosion in HXs.

6.4 Ocean thermal energy conversion (OTEC) system

Ocean thermal energy conversion (OTEC) is a process that can produce electricity by using the temperature difference between deep cold ocean water and warm tropical surface water (**Figure 7**). A large amount of seawater is pumped to run a power cycle and produce electricity. It is clean, environmentally sustainable and capable of providing large amounts of energy.

In tropical island communities, where a high percentage of electricity is oil-based, OTEC has become a commercially attractive option due to increased electricity cost, concern for global warming, and political commitment to energy security.

Global OTEC investment has surpassed $100 million USD for its research and development. It is estimated that the global resource has the potential to produce four times more electricity than global requirements. An offshore commercial OTEC plant can prevent the burning of 1.3 million barrels of oil each year. Carbon dioxide emission would be reduced by over half a million tons per year.

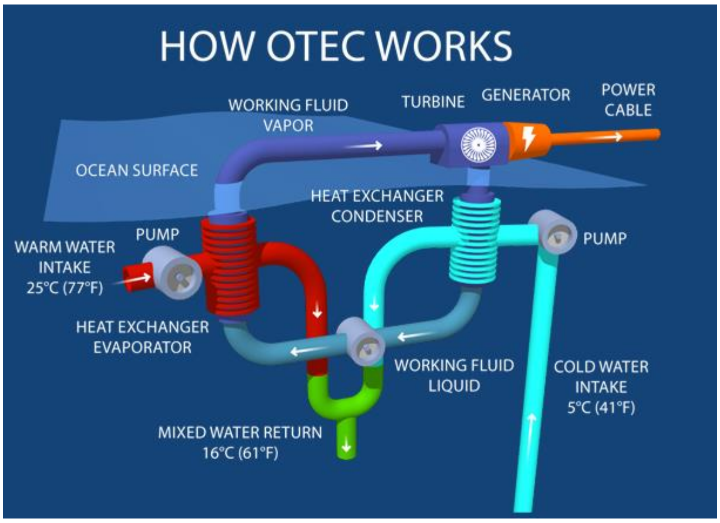

Figure 7: Closed cycle OTEC system (Makai, 2020)

Some of the challenges related to OTEC power plants are its low thermodynamic efficiency, the extremely large size of the plant, and its permanent location at sea. However, to make OTEC economically viable, bio-fouling and corrosion issues must be overcome. Materials that come into contact with ocean water become coated with organic and inorganic films, including microorganisms. These materials also undergo corrosion, which causes deleterious effects that compromise the integrity of the equipment.

According to Laity (1976), the thickness of biological film has a direct relation to heat transfer efficiency. He reported that if the film thickness is greater than 0.01 inch then heat transfer efficiency would reduce by about 50%. Increasing the size of the heat exchanger to improve the corrosion condition is not possible for OTEC plants due to their large size and very low thermodynamic efficiency. Increasing the seawater flow also has limitations because the heat transfer rate would increase nominally while the parasitic power demand could quickly pass the point of economic viability.

Perrigo and Jensen (1976) suggested five general approaches to fight bio-fouling and corrosion in OTEC systems.

- **Material specification and selection**

  This requires the selection and materials that impede or resist the growth of microorganisms and corrosion. There is plenty of information available on metal behavior and corrosion in the marine environment However, development of corrosions resistant materials has been significantly improved throughout the years.

- **Alteration of environment**

  Chemical manipulation can reduce the degradation of the heat transfer surface. But the size of the OTEC plant and the sheer volume of water being pumped require a different approach to solve the problem.

- **Surface coating**

  Both organic and inorganic coatings have been used to impede corrosion and biofouling in the marine environment. Their application in the OTEC system can improve overall system efficiency.

- **Electrochemical procedures**

  Anodic and cathodic protection, and chlorine generation have been used to prevent corrosion and fouling in marine and terrestrial systems. It is conceivable that a very small amount of impressed current may alter the biofouling behaviour of marine systems.

- **Preventive design**

  Preventive design is concerned with the effects of geometry, orientation, layout, configuration, and fluid flow characteristics. This method requires extensive knowledge on the anticorrosion designing principle.

There is also potential value in heat transfer enhancement in OTEC For a closed cycle OTEC plant, fluids with low boiling point are preferred due to the low-grade heat source. Various refrigerants such as ammonia, R134a, and propane have been successfully used in OTEC plants. Ammonia is the most common choice with a boiling temperature of -33°C at atmospheric pressure.

One major drawback of OTEC is its low efficiency, which is less than 10%. Improving heat transfer efficiency will drastically enhance this technology. So far, most of the heat transfer enhancement research has been done using water as a working fluid. Successful research on improving the heat transfer of refrigerant or organic fluids, this will have a huge impact on the OTEC sector.

GeoHex opportunity: GeoHex concept of improving heat transfer can be applied in the heat exchangers of this industry to improve OTEC low efficiency by enhancing heat transfer and, therefore, the cost. Moreover, there is a potential to use GeoHex coating technologies to reduce biofouling.

6.5 Water desalination plants

Desalination is the process of removing minerals from saline water. Desalination produces water suitable for human consumption and irrigation. It is also used in seagoing ships and submarines. Due to its power consumption, desalination is costlier than groundwater, water recycling, and water conservation. Currently, only 1% of the world population consumes water from desalination, but the UN expects by 2025, 14% of the world population will face water scarcity (Wikipedia, 2020). Dry countries such as Australia rely on desalination plants. Kuwait produces more water through desalination than any other country.

There are three major roles of heat exchangers in thermal desalination plants:

- Heat rejection;
- Heat recovery;
- Brine heating.

There are many types of desalination plant. For this document, a multi-stage flash distillation plant was considered (as shown in Figure 8) because the corrosion prevention method is similar to GeoHex. Malik et al. (2015) studied heat exchanger corrosion and material selection of multi-stage flash desalination plants. According to their research, more than 70% of corrosion-based heat exchanger failures in desalination plants occur in heat exchanger tubes. The brine heater is the part that has the highest chance of scale formation. Currently, 70/30 CuNi or modified 66/30/2/2 Cu-Ni-Fe-Mn alloy are used as brine heater tubes. Titanium tubing (ASTM B338) has also been used. For tube plate material, 90/10, Cu-Ni, naval brass, or Ni-Al bronze are the most adopted tube plate materials.

The heat recovery unit is the least vulnerable to corrosion. 90/10 CuNi is used in most of the recovery section of plants. 70/30 CuNi has been used in some higher temperature stages and 90/10 CuNi at low-temperature stages. Titanium has been reported to be used in only one plant.

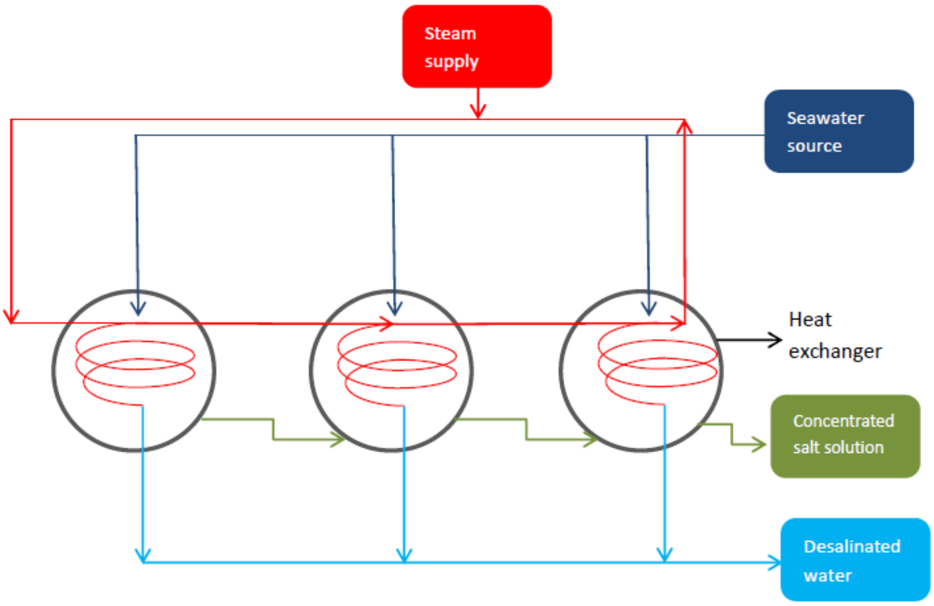

Figure 8: Multistage flash distilation plant

The heat rejection unit contains chlorinated water to fight biofouling. Titanium metal tubing (ASTM B338) is used in most of the plants, but in some plants, 90/10 CuNi and 70/30 CuNi are employed. Modified alloys such as Cu-Ni-Fe-Mn are gaining increasing applications as heat exchanger materials.

Plastic based heat exchangers can be an alternative to prevent corrosion. They are easy to construct, installation and erection costs are lower, and they can operate at top brine temperature (TBT) without fear of scale formation. The biggest drawback is the poor thermal conductance of plastic materials.

El-Dessouky, and Ettouney (1999) studied compact heat exchanger for a single effect mechanical vapour compression desalination system. Multiple tubing materials such as PTFE, high steel alloys, 90/10 and 70/30 cupronickel alloy and titanium were tested for determination of power consumption and specific heat transfer for the evaporator and preheater. After cost analysis, PTFE showed the lowest cost compared with the others.

Polymer compact heat exchangers (PCHE) are another option. Recently polymer film compact heat exchanger (PFCHE) using a thin film (100µm) has been considered to address the thermal conductivity deficiency (Zaheed and Jachuck, 2004). Due to excellent thermal, mechanical, chemical stability, polyether ether ketone (PEEK) has been adopted in PFCHE design.

Ni-P-PTFE composite coating is one of the proposed methods to reduce corrosion in the GeoHex project. It provides high wear resistance, corrosion resistance, high toughness, and roughness, and good lubrication properties (Grosjean et al., 2001). This coating has a wide temperature range up to 290°C, which makes it suitable to be applied in heating elements and heat exchangers.

Cheng et al. (2019) studied the effect of PTFE concentration on Ni-Cu-P composite coating and found that it showed good corrosion resistance. But they also observed that with the increase of pores in the coating due to increase in PTFE concentration, thermal conductivity, mechanical properties and wear resistance of the coating start to decrease. So, the concentration of PTFE must be kept within a certain limit. Overall, the implementation of PTFE coating has huge potential in the heat exchanger sector.

GeoHex opportunity: Therefore, GeoHex PTFE coating can be used in the HXs of desalination plants, provided the PTFE concentration can be kept limited to a certain level.

6.6 Waste heat recovery sector

Waste heat recovery is the collection of heat created as an undesired by-product of the operation of a piece of equipment or machinery to fill a desired purpose elsewhere. According to the United States Department of

Energy, up to 50% of energy burnt from all the fossil fuel burned in the U.S ends up in the atmosphere as waste heat. Research indicates that recovering waste heat could provide 20% of domestic electricity demand and reduce greenhouse gas emission by 20% (Rouse, 2020). Industrial processes are responsible for around 26% of primary European power consumption and are characterised by a multitude of energy losses. The global waste heat recovery (WHR) market is expected to surpass $65 billion by the end of 2021, with a compound annual growth rate (CAGR) of 6.9% (Markets and Markets, 2016). Another report suggests that a compound annual growth rate of 4.8% by the end of 2025 (QYResearch, 2019). Currently, Europe leads the market related to WHR with a 38% share of the global market as of 2012 (Markets and Markets, 2018). The Asia Pacific region has been experiencing the highest growth rate in the last few years of about 10% per annum, with China and India having the highest amount of WHR installation. In the industrial sector, the most common application of WHR is preheating and power generation via the thermodynamic bottoming cycle. Heat recovery requires heat demand in the industrial site, but electricity generation is more favourable in terms of energy management. It provides greater economic and emission savings. If heat recovery takes place in thermal form from the combustion of natural gas, 1 MWh of thermal energy recovered will avoid 0.202 tons of carbon dioxide emitted in the air. The same energy converted to electricity would have an emission factor of 0.406-ton carbon dioxide / Mhe (Markets and Markets, 2018).

Campana et al. (2013) discuss the prospects of ORC based waste heat recovery systems in 27 countries of the European Union. According to their study, about 20000 GWh of thermal energy per year can be recovered, and 7.6 M tons of CO_2 can be saved by the application of ORC. Their study predicts about 2705 MW of gross power. The ORC potential can lead up to 21.6 TWh per year of electricity production. Almost 1.85 billion of euros and over 8.1 million tons of greenhouse gas emission, which is around 2% of European industry consumption.

Bianchi and De Pascale (2011) found that among ORC, Stirling engines, thermo-electric, Micro-Rankine cycle, and inverted Brayton cycles, ORC was the best performing technology for heat recovery and power generation using heat sources from 200-400°C.

A comparison report was published from the H-REII project (Rossetti, 2010), where it was established that cement, glass, steel, and oil & gas industries were the most suitable industries for heat recovery to power production (Figure 9).

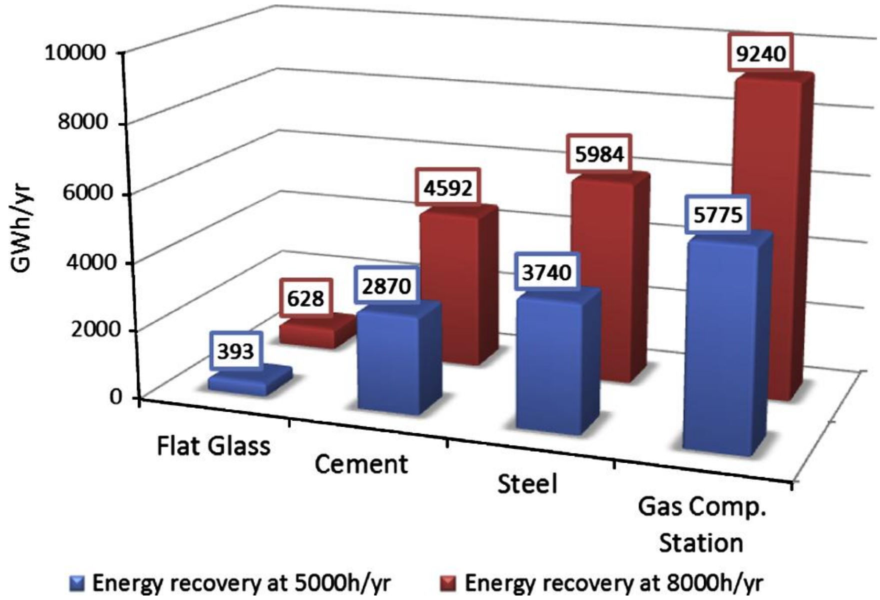

Figure 9: Annual Energy Recovery in EU27 industries

Most of the research conducted on ORC based heat recovery is focused on identifying the most suitable industry, estimating gross power output, environmental impact, cost analysis, etc. No significant literature was found discussing specifically the heat exchanger characteristics of ORC based heat recovery systems.

GeoHex Opportunity: For low to medium grade heat sources used in heat recovery units, GeoHex solutions have potential application. The GeoHex concept of the boiling and condensing surface enhancement methods for increasing heat-transfer would be applicable due to the similar thermodynamic cycle, working fluid, and temperature range.

6.7 Industrial wastewater treatment plants

Wastewater treatment, also called sewage treatment, is the removal of impurities from wastewater, or sewage, before they reach aquifers or natural bodies of water such as rivers, lakes, estuaries, and oceans. Water is said to be polluted when it contains enough impurities to make it unfit for a particular use, such as drinking, swimming, fishing, etc.

According to Markets and Markets (2018), the wastewater treatment market is expected to reach 65.1 billion USD by 2024, from an estimated 48.5 billion USD in 2019 at a CAGR of 6.1% (**Figure 10**). This would include used or sewerage water from households and industries.

The quality of treated water depends on the presence of total dissolved solids (TDS), hardness, pH, etc. Industrial wastewater can come from power, oil & gas, chemical, pharmaceutical, food, pulp and paper, and mining.

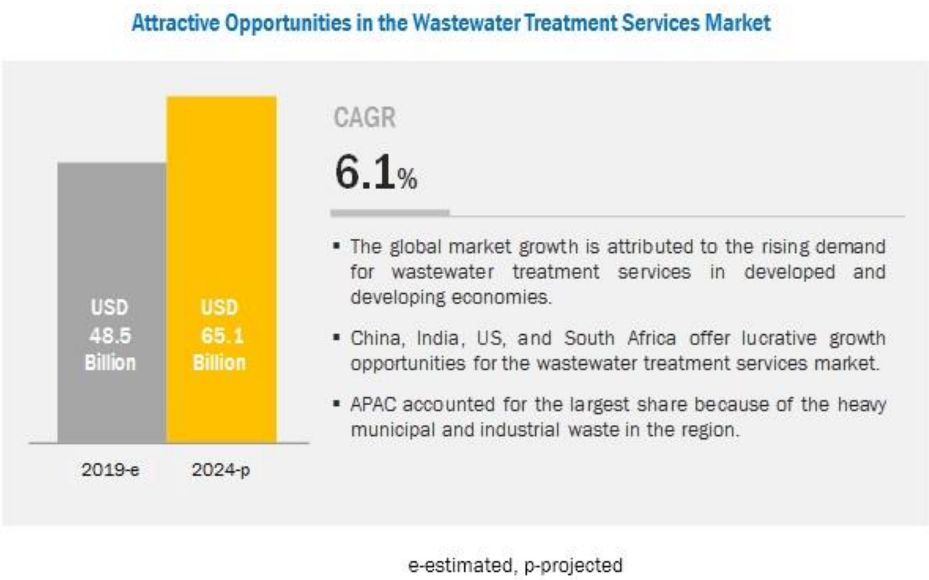

Figure 10: Wastewater treatment market estimation

Power generation is expected to see the fastest growth during the forecast period. The municipal segment is expected to be the largest end-user of wastewater treatment during the forecast period.

The Asia Pacific region will account for the largest share of the global wastewater treatment service market due to the increasing demand from municipals and power generation (**Figure 11**). Also increasing the amount of municipal wastage, water scarcity will be the driving force for the growth of wastewater treatment services in Asia Pacific.

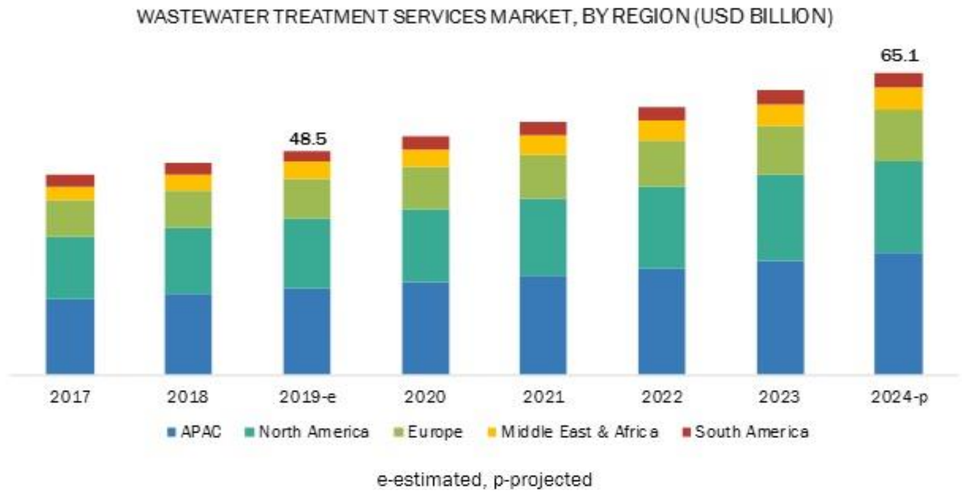

Figure 11: Region wise market demand of wastewater treatment

Biofouling is a common phenomenon in water treatment. It is the deposition and growth of living organisms on heat transfer surfaces. In water treatment, it is almost always caused by microorganisms. Titan et al. (2012) studied the effect of silica dioxide particles on the evolution of biofouling. They examined a plate type heat exchanger used in a waste heat utilisation heat pump system and found about 60% reduction in heat transfer coefficient after 40 days. SiO_2 is the most common inorganic particle found in sewerage water. The relation between biofilm formation and SiO_2 concentration was studied, and it was found that with the increase of SiO_2 concentration, the biofouling mass also increased. But the highest biofouling substance level and biofouling resistance were observed when the SiO_2 concentration was intermediate. Surface roughness played an important role in heat transfer. In the beginning, biofouling was small, so the conductive resistance due to biofouling was also small; in fact, the surface roughness provided by the fouling enhanced convective heat transfer. With time, biofouling mass increased, and the conductive resistance increased, with a decrease in the overall heat transfer coefficient. So, controlling the SiO_2 content will influence biofouling formation.

Many researchers are working on developing biofouling resistant materials. Tesler et al. (2015) worked on developing anti-fouling steel surfaces by electrodeposition of nanoporous tungsten oxide films. Tungsten oxide coatings are inherently super hydrophilic, but when they are converted to superhydrophobic, they remain non-wetting even after impingement with yttria-stabilised-zirconia particles, or exposure to ultraviolet light and extreme temperatures. Green alga *Chlamydomonas reinhardtii* was used as a model organism for aquatic fouling on tungsten oxide coated austenitic AISI 304 grade stainless steel substrate. Tungsten oxide -SLIPS (slippery liquid infused porous surface) and tungsten oxide -SHS (superhydrophobic surface) were tested and tungsten oxide -SLIPS showed the least amount of biofouling formation.

GeoHex opportunity: Hydrophobic and oleophobic surfaces are less prone to fouling. The porosity of the heat transfer surface is also responsible for fouling resistance. All of these methodologies are proposed in GeoHex. The GeoHex concepts may reduce biofouling in the wastewater treatment industry and also can increase the heat transfer.

6.8 Automotive sector

Automotive heat exchangers transfer heat between two mediums at different temperatures. In the case of an internal combustion engine, engine coolant flows in a circular motion through the radiator coil, and air flows past these coils. The global market for automotive heat exchangers is classified according to their applications, design types, and vehicle types.

The automotive heat exchanger market is expected to register a CAGR of 6% during 2020-2025. By 2014, the automotive sector acquired more than a 25% share of the total heat exchanger market. In terms of automotive production, 95.76 million units were produced in 2018 and this is expected to reach 115 million units by 2021.

Middle East and Asia Pacific region will be the major areas of interest due to increased demand (Mordor Intelligence, 2019a).

Generally, active or passive methods are used to improve heat transfer in heat exchangers (Rajput and Kulkarni, 2014; Kumar et al, 2013; Witry et al., 2003). Active methods require external power, which limits their applications. Active methods consist of mechanical assistance, surface vibration, fluid vibration, electrostatic fields, injection, suction, or jet impingement (Kumar et al, 2012). Passive methods require surface or geometrical modifications to the flow channel by incorporating inserts.

Borghino (2010) observed heat dissipation by applying a nanostructured coating. The coating produced a heat transfer coefficient ten times higher than with the uncoated surface, and heat dissipation four times faster than previously possible. Liu et al (2015) has shown the effects of surface characteristics such as nanoscale roughness, solid-liquid contact angle, and effective heat transfer ratio. Kumar et al. (2012) reported the heat transfer enhancement by nanostructured carbon nanotube coating (CNT). The application of the CNT coating on the surface enhances the heat flux. It was also found that CNT coating also increases heat transfer to some extent Kumar et al. (2013) used an aluminium fin coated with CNT using the PVD process. The heat transfer rate with and without the coating were compared, and a 5% increase was observed.

GeoHex opportunity: Multi-walled carbon nanotube coating has been proposed to enhance single-phase heat transfer for carbon steel. The GeoHex concept may be applied to HXs in this sector

6.9 Concentrated solar power (CSP) sector

Concentrated solar power (CSP) is a solar power generation system where sunlight is concentrated by mirrors or lenses onto a receiver. Electricity is generated when the concentrated light is converted to thermal energy, which then drives a steam turbine (**Figure 12**). It is a clean and sustainable energy source. International Energy Agency (IEA) has set an electricity generation target of 630 GW_e using CSP technology by 2050 (Guillot et al., 2012).

Spain (60%) and the USA (40%) are the main consumers of the CSP market. The world's largest CSP plant was commissioned in the USA in2014 (Ivanpah Dry Lake, CA) with 392 MWe that can power roughly 100,000 homes.

The heat transfer medium in CSP is called heat transfer fluid (HTF). There are six main types of HTF-

- Air and other gases;
- Water steam;
- Thermal oils;
- Organics;
- Molten salts;
- Liquid metals.

Molten salts are the most used HTF due to their high working temperature (>500°C) and heat capacity, low vapour pressure, and good thermal and physical properties at elevated temperatures.

Fernandez et al. (2012) studied the corrosion effect of 60% $NaNO_3$ and 40% KNO_3 in different stainless steels and low 1% Cr steel in a working temperature of CPS plants at 390°C and 550°C. Corrosion can takes place due to the presence of a thermal gradient in the melt. It can trigger fouling and plugging in a circulating circuit. The molten salt corrosion is similar to aqueous corrosion (Bradford, 1987). It was found that at 390°C, T22 steel showed major weight gain; however, it was still suitable for application in the CSP sector. The temperature was increased to 550°C to match the operating condition of the CSP tower. At this temperature, AISI 304 steel showed acceptable result, but ferritic steel showed major corrosion. T22 steel could not survive an 800 hour test in the HTF mixture without developing corrosion. $MgFe_2O_4$, $FeCrO_4$, and Fe_2O_3 were observed as principal corrosion products. Sodium carbonate and sodium ferrite were also found.

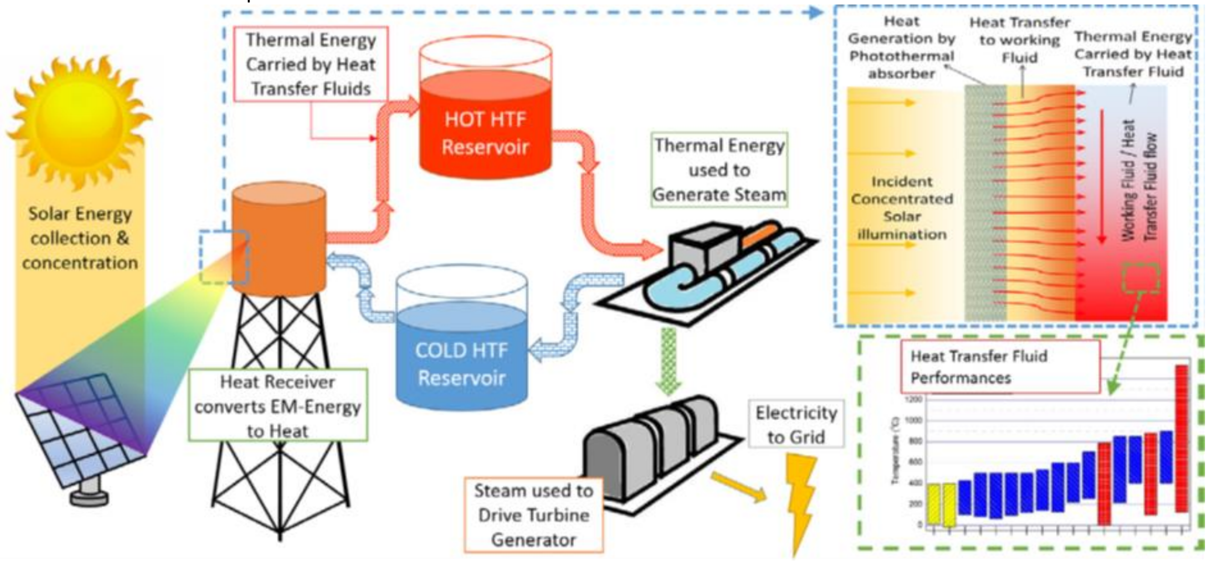

Figure 12: Concentrated Solar Power plant

The major difference between geothermal and concentrated solar power is their operating temperature. Geothermal plants operate at considerably lower temperatures than CSP. In high-temperature geothermal sources, the geofluid itself acts as a working fluid wherein low-temperature sources, various low boiling point working fluids are utilised. The working fluid is another significant variable that is different in both cases. Not a lot of research has been done on scaling issues in the CSP sector. The corrosion materials also differ in both cases.

GeoHex opportunity: Even though the power cycle of concentrated solar plants is similar to geothermal power plants, their working temperature, heat source, working fluid are very different. The corrosive and scale-forming materials are also different. But the GeoHex materials with superhydrophobic and superoleophobicity properties may be implemented in the condensers of concentrated solar plants to improve heat transfer.

7 CONCLUSIONS

This report describes GeoHex opportunities in the geothermal energy sectors and beyond, formalising the GeoHex opportunities identified in deliverables D1.1 to D1.5.

GeoHex outputs can addresss opportunities in the geothermal sector, including; ORC based binary cycle power plants, Enhanced geothermal systems (EGSs), combined power plants (flash steam and binary cascade), and geothermal desalination plants.

Our literature review showed that there are industries beyond geothermal sectors where GeoHex concepts have opportunities and can be applied to improve scaling and corrosions effects as well as heat transfer. These include:

- Dairy industry;
- Petrochemical industry and oil refineries;
- Ocean thermal energy conversion (OTEC) systems;
- Desalination plants;
- Waste heat recovery sector;
- Industrial wastewater treatment plants;
- Automotive sector;
- Concentrated solar power.

Deliverables D1.1 to D1.5 respectively:

- Identified the types of heat exchanger most relevant for the geothermal sector.

- Reviewed the state-of-the-art for heat exchangers.
- Reviewed the fundamental science of boiling in order to identify the characteristics of an ideal boiling surface to improve heat transfer.
- Reviewed the science behind wetting with a focus on the non-wetting behaviour of fluids so that higher heat transfer can be assured through dropwise condensation, in order to identify the ideal condensing surface.
- Summarised the thermophysical properties of various working fluids.

From the review of the deliverables D1.1 to D1.5, the following important findings were noted to formalise the GeoHex opportunities:

i) Deliverable 1.1 found that for low and mid-range heat source temperatures (<150-200°C), the hydrofluorocarbons (HFC) R134a and R245fa are preferable. Therefore, the choices of the working fluids are fine with the input temperature 170°C (GeoHex monthly meeting notes, 05 March 2020) of the brine in the GeoHex project. However, in D1.5 R134a was identified as a wet fluid and dry fluids are preferable for power generation. GeoHex concepts will improve the HX corrosion, scaling, and heat transfer performance and thereby will improve the plant efficiency, cost, etc; however, use of wet working fluid may reduce the overall plant efficiency.

ii) Regarding heat exchanger technologies, D1.1 reported through their review that the most relevant heat exchangers for large-scale geothermal power plants are shell-and-tube heat exchangers. However, plate-type heat exchangers are the most cost-effective (lower heat transfer surface). Therefore, it was proposed in D1.1 to test both types HXs in the GeoHex project.

iii) D1.1 proposed some configurations for the GeoHex tests, which are; 'For phase change HXs (evaporator, condensers) and single-phase HXs-, use carbon steel shell and tube heat exchanger and water-cooled condensers. And for plate type use stainless steel for evaporators and single-phase HXs, and air-cooled condensers with Fin - and -Tube HX.

iv) In D1.3 to Identify the characteristics of optimum surfaces for flow boiling heat transfer related to ORC working fluid, it is found in this review that there is a lack of engineering knowledge available in the literature regarding the surface enhancement. Since adequate data are not available in the literature for the design of structures and to inform design parameters, it was therefore concluded in D1.3 that the design parameters would be optimised with data obtained in the GeoHex program.

v) The D1.3 review identified that there is a lack of data regarding the effect of process parameters on heat transfer, corrosion performance, long-term test data to prove the longevity of any coatings. And most studies investigated heat transfer enhancement with water as the working fluid, rather than fluids more appropriate for heat exchangers. It is concluded in D1.3 that despite the lack of data available in the literature, the reviewed data so far obtained can still be useful as a starting point for coating development in the GeoHex program.

vi) In D1.2, an FMEA for the GeoHex heat exchangers was conducted, and risks were generally determined to be low; mitigations were identified to further reduce the risks. These included appropriate maintenance, including water treatment and operational control, as well as considerations in design.

Therefore, GeoHex opportunities regarding the improvement of corrosion, scaling, enhance heat transfer by developing coating materials for the HXs used in the geothermal sectors and beyond can be maintained throughout the project, mitigating the identified risks, considering the recommendations made in the various deliverables (D1.1 to D1.5).

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