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| **Project acronym:** | **GeoHex** |
| **Project title:** | Advanced material for cost-efficient and enhanced heat exchange performance for geothermal application |
| **Activity:** | LC-CS3-RES-1-2019-2020 Developing the next generation of renewable energy technologies |
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| **WP7** | **Demonstration of GeoHex enabled HX materials** |

# D7.8 Environmental performance of GeoHex enabled HXs

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| **Version:** | V2 | |
| **Abstract** | The current report evaluates the environmental impacts of six GeoHex enabled and six standard Heat Exchangers (HXs) and analyse the carbon and environmental footprints of these GeoHex enabled HXs for adopting GeoHex materials. | |

# REVISION HISTORY

| Version | Date | Main Authors/Contributors | Description of changes |
|---|---|---|---|
| V1 | 04/10/2023 | M A H Chowdhury | First version created |
| V2 | 16/10/2023 | M Ahmed | Revised and reviewed with the latest updated Heat transfer performance results of HXs |

[1] Dissemination level security:

**PU** – Public (e.g. on website, for publication etc.) / **PP** – Restricted to other programme participants (incl. Commission services) /

**RE** – Restricted to a group specified by the consortium (incl. Commission services) / **CO** – confidential, only for members of the consortium (incl. Commission services)

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# Executive Summary

The carbon intensity in the geothermal sector is relatively low compared to other forms of energy generation using fossil fuels. The carbon emissions primarily result from the construction and maintenance of geothermal power plants and the drilling of geothermal wells. The main goal of this task is to evaluate the environmental impacts of six GeoHex enabled and six standard Heat Exchangers (HXs) and analyse the carbon and environmental footprints of these GeoHex enabled HXs for adopting GeoHex materials.

The cradle-to-grave system boundary is considered in this study. This study's functional unit is considered as 1 $m^2$ heat exchanged surface area of these HXs. Based on the inventoried data of these HXs for construction, use and end-of-life phases, the environmental impacts of six GeoHex enabled and six standard HXs in three application areas (preheater, condenser and evaporator) with two technology options (tubular and plate) were performed using the SimaPro 9.5.0.0 LCA tool, considering the impact assessment methodology IMPACT 2002+ version 2.15. It has been demonstrated that the carbon footprint savings for adopting GeoHex enabled plate and tubular types of evaporators and tubular type preheater are about 6.5%, 12.2% and 13.5%, respectively, instead of using the respective standard HXs.

# Objectives Met

The deliverable contributed towards the work package WP7 objective:

- To demonstrate the environmental performance of GeoHex enabled heat exchangers (for geothermal application) compared to the heat exchangers made by SOA materials.

**Version: 2**

**Date:** 18 October 2023

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# List of Acronyms

| | |
|---|---|
| APOS | Allocation at Point of Substitution |
| CO | Condenser |
| EV | Evaporator |
| HXs | Heat Exchangers |
| IMPACT | IMPact Assessment of Chemical Toxics |
| ISO | International Organization for Standardization |
| LCA | Life Cycle Assessment |
| LCI | Life Cycle Inventory |
| LCIA | Life Cycle Impact Assessment |
| PH | Preheater |
| PL | Plate |
| SOA | State-of-the-art |
| TU | Tubular |

# 1. INTRODUCTION

Energy-related global $CO_2$ emissions has been rebounded to 36.6 Gt in 2021, the largest ever annual rise in emissions[2]. The geothermal energy sector is one of the key solutions to reducing greenhouse gas emissions and achieving the sustainable energy goals. One of the objectives of GeoHex project is to demonstrate the environmental performances of GeoHex enabled HXs for geothermal application compared to the HXs made by standard or state of art (SOA) materials.

In GeoHex project, various types of materials have been investigated for improving the heat transfer coefficient and corrosion-resistant properties in geothermal heat exchanger (HX) systems. For demonstrating GeoHex potentialities, 6 standard and 6 GeoHex enabled HXs in three application areas (preheater, condenser and evaporator) and with two technology options (Tubular and Plate) have been developed under tasks 7.1-7.3. Table 1.1 lists these 12 HXs with their respective capacities, tube and plate material types and grades, and HX ID for 6 GeoHex enabled and 6 standard HXs.

**Table 1.1 –** Application areas, technology options and capacities of 12 Standard and GeoHex enabled HXs

| Application area | Technology option | Capacity (kW) | Type & Grade of tube and plate materials | HX category | HX ID |
|---|---|---|---|---|---|
| Preheater (PH) | Tubular (TU) | 20 | CS: S275JR | Standard (STD) | PH_TU_STD |
| | | | | GeoHex enabled (GeoHex) | PH_TU_GeoHex |
| | Plate (PL) | 60 | SS:316L | Standard (STD) | PH_PL_STD |
| | | | | GeoHex enabled (GeoHex) | PH_PL_GeoHex |
| Condenser (CO) | Tubular (TU) | 9.5 | CS: S275JR | Standard (STD) | CO_TU_STD |
| | | | | GeoHex enabled (GeoHex) | CO_TU_GeoHex |
| | Plate (PL) | 53 | SS:316L | Standard (STD) | CO_PL_STD |
| | | | | GeoHex enabled (GeoHex) | CO_PL_GeoHex |
| Evaporator (EV) | Tubular (TU) | 5 | CS: S275JR | Standard (STD) | EV_TU_STD |
| | | | | GeoHex enabled (GeoHex) | EV_TU_GeoHex |
| | Plate (PL) | 45 | SS:316L | Standard (STD) | EV_PL_STD |
| | | | | GeoHex enabled (GeoHex) | EV_PL_GeoHex |

For adopting GeoHex materials in 6 GeoHex enabled HXs, it is expected that less materials are required for these HXs due to the increased heat transfer coefficient and hence its environmental footprint is expected to be improved as compared with standard HXs (without adopting GeoHex materials). This study aims to evaluate the environmental impacts and compare the results of carbon and environmental footprints of 6 GeoHex enabled and 6 standard HXs. The functional unit of this study is considered as 1 $m^2$ heat exchanged surface area of these HXs. The scope of this life cycle assessment (LCA) study is to consider the cradle-to-grave system boundary and is presented in Figure 1.1.

[2] World Energy Outlook 2022; IEA November 2022; www.iea.org accessed 17 August 2023.

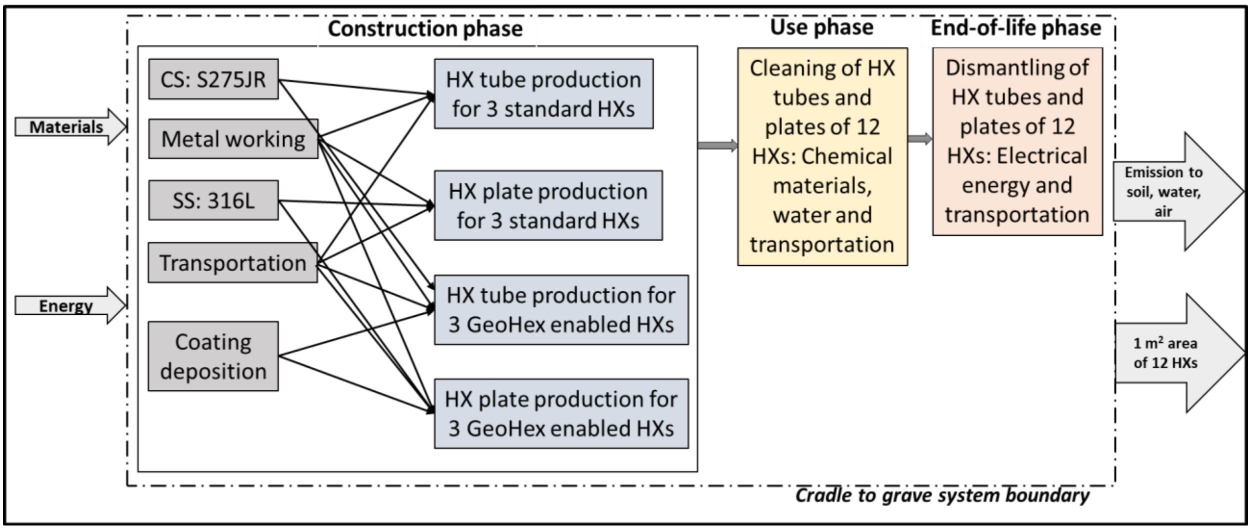


**Figure 1.1 –** A cradle to grave system boundary of life cycle assessment (LCA) study of 12 HXs

The intended audiences of this study are listed below:

- Heat exchanger material manufacturers
- Geothermal plant operators
- Policy makers in Geothermal industries
- Stakeholders in Geothermal industries
- Environmental agencies
- Consortium members
- European Commission

Section 2 describes LCA methodology and overall scheme of the impact assessment methodology IMPACT 2002+ V2.15. The data inventories of three plate and three tubular types GeoHex enabled and three plate and three tubular types standard HXs during construction, use and end-of-life phases are given in section 3. The environmental performance results of these HXs are presented in section 4. In section 5, the results of carbon and environmental footprints of three plate and three tubular types HXs with and without adoption of GeoHex materials are concluded.

# 2. LCA METHODOLOGY AND IMPACT ASSESSMENT

## 2.1 LCA Framework and Tool

Life Cycle Assessment (LCA) is a methodology for assessing the environmental impacts of a product or service throughout its entire life cycle from extraction of raw materials through design and production, packaging and distribution, use and maintenance, and disposal or recycling. It provides a holistic approach to evaluating environmental performance by considering the potential environmental impacts from all stages of manufacture, product use and end-of-life stages. This LCA methodology was standardised in the 1990s by the International Organisation for Standardization (ISO), which comprises mainly two standards: ISO 14040[3] and 14044[4] and is still updated and extended regularly. It involves the compilation of relevant inputs and outputs in the context of the goal and scope of the study, subsequent evaluation of their associated environmental impacts using an appropriate impact assessment methodology and finally, interpretation of the results with respect to the aims of the analysis.

The framework of LCA methodology comprises four stages, shown in Figure 2.1:

i) goal and scope definition,

ii) inventory analysis,

iii) impact assessment and

iv) interpretation

The first stage of an LCA is the goal and scope of the study, which must be defined before any collection of life cycle inventory data. The second stage of an LCA is the inventory analysis when the quality of the inventory data gathered is organised and assessed. In the third stage of an LCA study, an appropriate life cycle impact assessment (LCIA) method is considered for evaluating the potential environmental impacts such as global warming potential and other impacts from the list of the following LCIA methodologies: CML-IA baseline, IMPACT World+, IMPACT 2002+, ReCiPe 2016, ILCD 2011 and others. The interpretation is the last stage of an LCA, where the findings of the inventory analysis and the impact assessment results are analysed with the defined goal and scope of the study and finally drawn conclusions and recommendations.

[3] ISO 14040 - Environmental Management - Life Cycle Assessment - Principles and Framework. Geneva. (2006a).

[4] ISO 14044 - Environmental Management - Life Cycle Assessment - Requirements and Guidelines. Geneva. (2006b).

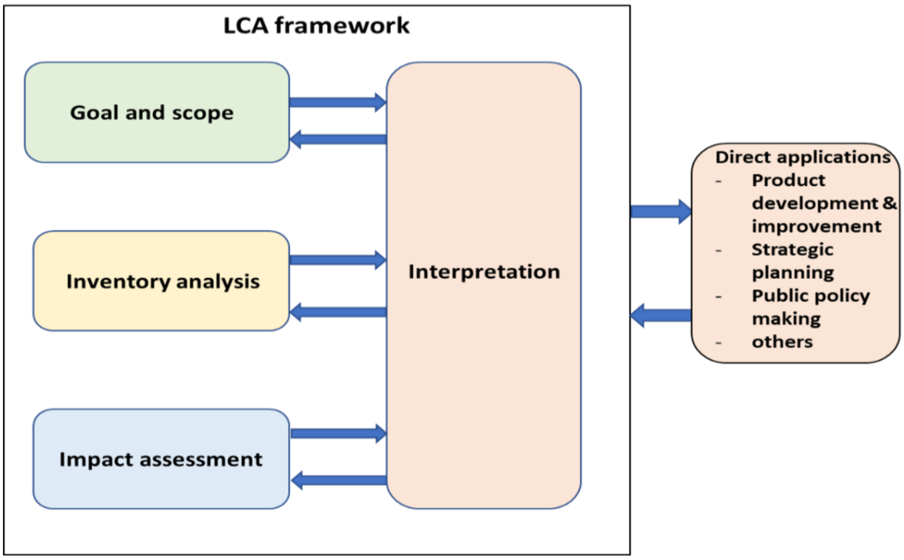


**Figure 2.1 -** An LCA framework

To perform LCA analysis of the intended study, we will use SimaPro 9.5.0.0, a LCA software tool allowing users to build LCA models of the products or processes over its entire life cycle, from raw material extraction to end-of-life disposal. The key functionalities of SimaPro LCA tool are as follows:

1. Building LCA models: SimaPro allows users to create LCA models of products or processes using a graphical interface. Users can enter data on raw materials, energy inputs, and outputs of each life cycle stage, and link these stages to create a complete life cycle model.
2. Accessing databases: SimaPro provides access to a variety of databases such as ecoinvent and others that contain data on materials, processes, and several impact assessment methods. This data can be used to build LCA models quickly and easily.
3. Customising data: Users can modify the data in the databases or add their own data to create customized LCA models that reflect their specific needs.
4. Calculating environmental impacts: SimaPro uses established impact assessment methods such as ReCiPe or IMPACT to calculate the environmental impacts of LCA models. It provides a wide range of impact categories, including climate change, water use, and toxicity.
5. Analysing results: SimaPro allows users to analyse and visualize the results of their LCA studies using various output formats, such as tables, graphs, and reports. This helps users to understand the environmental performance of their products or processes and identify areas for improvement.
6. Comparing scenarios: SimaPro allows users to compare different scenarios to assess the potential environmental impact of different choices. For example, users can compare the impact of using different materials, changing the production process, or altering the end-of-life disposal method.
7. Sharing results: SimaPro allows users to export LCA models and results in various formats, such as Excel, PDF, or CSV. This makes it easy to share results with stakeholders or use them in other software tools.

Overall, SimaPro is a powerful tool for conducting LCA studies, and its user-friendly interface, customisable data, and comprehensive analysis capabilities make it a popular choice for assessing and improving the environmental performance of its products or processes.

## 2.2 Impact Assessment

Life Cycle Impact Assessment (LCIA) is the phase in an LCA where the inputs and outputs of elementary flows have been collected and reported in the inventory and stored in an LCA tool. For translating the life cycle inventory (LCI) data of a product or a process to the potential environmental impacts, this study has selected

LCIA methodology: IMPACT2002+ V2.15[5]. This methodology proposes a feasible implementation of a combined midpoint/damage approach, linking all types of life cycle inventory results (elementary flows and other interventions) via 15 midpoint impact categories to four damage categories. Figure 2.2 shows the overall scheme of the IMPACT 2002+ framework, linking LCI results via 15 midpoints (Carcinogens, non-carcinogens, respiratory inorganics, ionising radiation, ozone layer depletion, respiratory organics, aquatic ecotoxicity, terrestrial ecotoxicity, aquatic acidification, aquatic eutrophication, terrestrial acid/nutri, land occupation, global warming, non-renewable energy, and mineral extraction to 4 damage categories (human health, ecosystem quality, climate change and resources). Following characterisation, normalisation and weighting of environmental impacts can also be performed. However, they are not compulsory parts of an LCA, and are therefore excluded for this study.

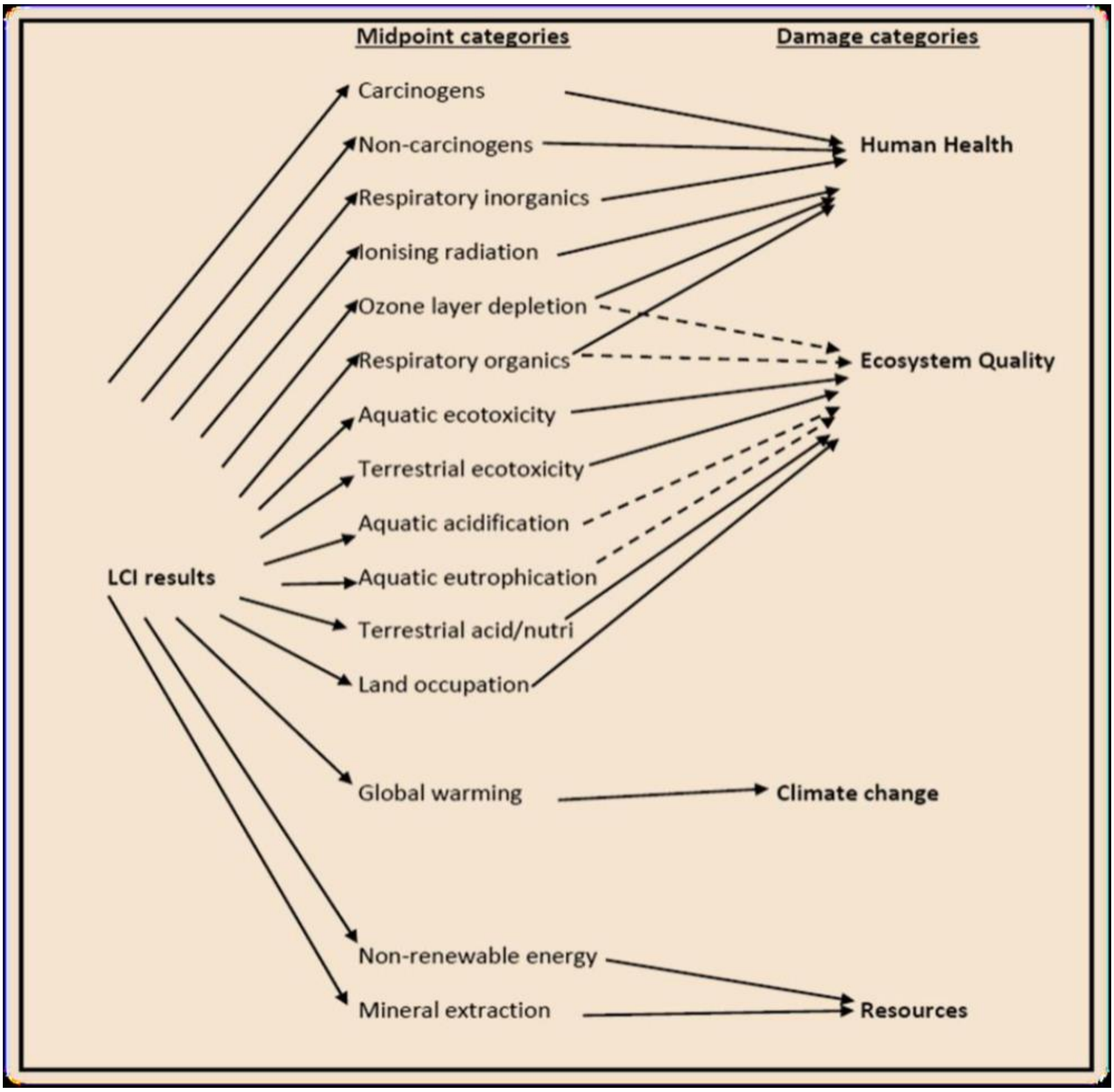


**Figure 2.2 –** Overall scheme of the IMPACT 2002+ framework.

[5] Jolliet O, Margni M, Charles R, Humbert S, Payet J, Rebitzer G, Rosenbaum R (2003) IMPACT 2002+: a new life cycle impact assessment methodology. Int J Life Cycle Assess 8:324–330.

The ecoinvent v3 database contains LCI data from various sectors such as energy production, transport, building materials, production of chemicals, metal production and fruit and vegetables. The entire database consists of over 20,000 interlinked datasets, each of which describes a life cycle inventory on a process level. SimaPro provides eight libraries that each contain all the processes that are found in the ecoinvent database but use different system models and contain either unit or system processes. The four ecoinvent system models are allocation at point of substitution (APOS), cut-off by classification, consequential and cut-off EN15804. In this study, cut-off system model using unit processes has been used for various background processes available in ecoinvent v3.9.1 database.

# 3. DATA INVENTORIES

The deliverable D7.1 reported the design specifications of three plate and three tubular types HXs in three application areas (preheater, evaporator and condenser). Each HX is manufactured twice for a total of 12 HXs - 6 HXs (three plate and three tubular) are considered as standard HXs without adoption of GeoHex materials and the other 6 HXs are considered as GeoHex enabled HXs with adoption of GeoHex materials.

In GeoHex enabled preheaters (PH_PL_GeoHex and PH_TU_GeoHex), amorphous metal based (GHX036) and Ni-P/Ni-P-PTFE duplex (HPHP) GeoHex coating materials have been applied to plate and tubular type, respectively for enhancing the heat transfer performance and anti-scaling and anti-corrosion performances to mitigate fouling and corrosion caused by geothermal brine. Tutoprom Bright materials with $SiO_2$ nanoparticles (Tutoprom_SMS35) have been applied in both tubular and plate types GeoHex enabled condensers (CO_TU_GeoHex and CO_PL_GeoHex) using sol-get Stober process for promoting robust droplet condensation for ORC working fluids (R134a and R1233zd) and therefore increase heat transfer performances. Doped $Al_2O_3$-$TiO_2$ composite coating materials (HSP-3.6-150) have been applied to both plate and tubular type evaporators (EV_PL_GeoHex and EV_TU_GeoHex) for promoting robust nucleate boiling for the ORC working fluids (R134a and R1233zd) and therefore increase the heat transfer performances. The details of adopting GeoHex materials in tubular and plate type preheaters, condensers and evaporators are reported in the deliverable report D7.3 (Delivery of 6 exchangers with GeoHex materials).

three plate and three tubular types standard HXs made with stainless steel (316L) and carbon steel (S275JR), respectively, were tested in mini ORC plant at CEA (task 7.3) facilities for determining the heat transfer coefficient (HTC) and scaling and corrosion-resistant properties and presented the results in the deliverable D7.5 (Test report on HXs based on SOA materials). Three plate and three tubular types GeoHex enabled HXs were also tested in the same mini ORC plant and obtained the HTC and corrosion and scaling-resistant properties and are reported in the deliverable D7.6 (Test report on HXs based on GeoHex materials). The deliverable D7.5 reports the heat transfer results of the 6 standard HXs (PH_TU_STD, PH_PL_STD, CO_TU_STD, CO_PL_STD, EV_TU_STD, and EV_PL_STD) made with standard materials carbon steel (S275JR) for tubular HXs and stainless steel (316L) for plate type HXs. The heat transfer performance results of these 6 standard HXs are considered as the baseline performances those will be compared with the results of heat transfer performances of 6 GeoHex enabled HXs (PH_TU_GeoHex, PH_PL_GeoHex, CO_TU_GeoHex, CO_PL_GeoHex, EV_TU_GeoHex, and EV_PL_GeoHex) from the outcomes of the deliverable D7.6. The enhancement or degradation of HTCs of 6 GeoHex enabled HXs have been evaluated compared to respective 6 standard HXs. The respective GeoHex materials, deposition method, and enhancement of HTCs (%) of three tubular and three plate GeoHex enabled HXs are given in Table 3.1. The respective coating deposition data per $m^2$ area for three GeoHex enabled HXs have been gathered from the deliverables D5.3 and D5.4.

**Table 3.1 –** HTC enhancement or degradation results of 6 GeoHex enabled HXs

| Items | GeoHex enabled Plate HXs | | | GeoHex enabled Tubular HXs | | |
|---|---|---|---|---|---|---|
| | Preheater | Condenser | Evaporator | Preheater | Condenser | Evaporator |
| GeoHex materials | GHX036 | Tutoprom_SMS35 | HSP-3.6-150 | HPHP | Tutoprom_SMS35 | HSP-3.6-150 |
| Deposition method | PVD | Dip Coating | Plasma spray | ENP | Dip Coating | Plasma spray |
| HTC enhancement or degradation (%) | -3.6 | 3.5 | 53.8 | 16.7 | 2.0 | 24.2 |

Due to the unavailability of the material transportation, cleaning material and dismantling energy data, the following data have been assumed for estimating the resource and energy consumption during construction, use and end-of-life phases and listed in Table 3.2.

**Table 3.2 –** Assumptions made for transportation, cleaning material and dismantling energy.

| Items | Unit | Amount |
|---|---|---|
| Average road transportation distance for raw materials and HXs | km | 200 |
| Average amount of cleaning material | kg / $m^2$ | 1 |
| Average amount of tap water used | litre / $m^2$ | 50 |
| Frequency of cleaning per year | - | 2 |
| Dismantling energy | MJ / kg | 5 |
| Estimated lifetime of the HXs | y | 10 |

## 3.1 Plate Heat Exchangers

The detailed design specifications of three plate-type HXs (preheater, evaporator and condenser) are reported in the deliverable D7.1. The important features and specifications of these plate types HXs are listed in Table 3.3.

**Table 3.3 –** Important features and specifications of three Plate Heat Exchangers

| Parameters | Unit | Plate Heat Exchangers | | |
|---|---|---|---|---|
| | | **Preheater (PH_PL)** | **Evaporator (EV_PL)** | **Condenser (CO_PL)** |
| Manufacturers | - | Nexson | Alfa Laval (M6-MFD) | Alfa Laval (M6-FG) |
| Technology options | - | Plate & gaskets | Plate & gaskets | Plate & gaskets |
| Capacity | kW | 60 | 45 | 53 |
| Plate material type and grade | - | Stainless Steel: 316L | Stainless Steel: 316L | Stainless Steel: 316L |
| GeoHex materials on one side of the plate | - | GHX036 (Si:Ta:Fe) | GHX036 (Si:Ta:Fe) | Tutorprom Bright materials with SiO2 nanoparticles |
| GeoHex materials on other side of the plate | - | HST-10-150 (metal oxide nanoporous) | HSP-3.6 (Fe-doped Al2O3-TiO2); | - |
| Number of plate | - | 18 | 32 | 23 |
| Area of the plate | $m^2$ | 0.25x0.49 | 0.25x0.75 | 0.25x0.75 |
| Corrugation height | mm | 2.8 | 3.1 | 1.8 |
| Corrugation pitch | mm | 10 to 20 | 11.4 | 5.6 |
| Thickness of the wall of the plates | mm | 0.6 | 0.5 | 0.5 |
| Heat exchange surface area | $m^2$ | 0.6 | 4.3 | 3.3 |
| Temperature range | $^0C$ | 120 | 170-120 | 72.5-41.5 |
| Maximum pressure* | bar | 2.7 | 16.45 | 7.77 |
| Overall heat transfer coefficient | $W\ m^{-2}\ K^{-1}$ | 2270 | 325 | 1800 |
| Fluid types | - | Brine/water | Thermal oil/ORC fluid | ORC fluid/Water |

*on working fluid side for evaporator & condenser and on brine side for preheater.

The masses of the plate materials for 60 kW preheater, 53 kW condenser and 45 kW evaporator have been calculated using the respective lengths, heights and thicknesses of the respective plates given in Table 3.3 and obtained 10.45, 17.03 and 23.13 kg, respectively. The material, transportation and energy flows in terms of functional unit of 1 $m^2$ have been calculated for three standard and three GeoHex enabled plate type HXs (preheater, evaporator and condenser) in the construction, use and end-of-life phases using the data given in Tables 3.1, 3.2 and 3.3 and are listed in Tables 3.4, 3.5 and 3.6, respectively.

**Table 3.4 –** Functional mass, energy and transportation flows of 6 plate HXs during construction phase.

| Process name | Units | Functional Material and other flows during construction phase of 6 plate HXs | | | | | |
|---|---|---|---|---|---|---|---|
| | | PH (60 kW) | | CO (53 kW) | | EV (45 kW) | |
| | | STD | GeoHex | STD | GeoHex | STD | GeoHex |
| Plate material | $kg/m^2$ | 17.42 | 18.05 | 5.16 | 4.98 | 5.38 | 2.49 |
| Metal working | $kg/m^2$ | 17.42 | 18.05 | 5.16 | 4.98 | 5.38 | 2.49 |
| Transportation | $tkm/m^2$ | 3.48 | 3.61 | 1.03 | 1.00 | 1.08 | 0.50 |

**Table 3.5 -** Functional mass and transportation flows of 6 plate HXs during use phase.

| Process name | Units | Functional Material and other flows during use phase of 6 plate HXs | | | | | |
|---|---|---|---|---|---|---|---|
| | | PH (60 kW) | | CO (53 kW) | | EV (45 kW) | |
| | | STD | GeoHex | STD | GeoHex | STD | GeoHex |
| Cleaning material | $kg/m^2$ | 20 | 20.72 | 20 | 19.30 | 20 | 9.24 |
| Tap water | $litre/m^2$ | 1000 | 1036 | 1000 | 965 | 1000 | 462 |
| Transportation | $tkm/m^2$ | 7.48 | 7.75 | 5.03 | 4.86 | 5.08 | 2.35 |

**Table 3.6 -** Functional energy and transportation flows of 6 plate HXs during end-of-life phase.

| Process name | Units | Functional Material and other flows during end of life phase of 6 plate HXs | | | | | |
|---|---|---|---|---|---|---|---|
| | | PH (60 kW) | | CO (53 kW) | | EV (45 kW) | |
| | | STD | GeoHex | STD | GeoHex | STD | GeoHex |
| Electrical energy | $MJ/m^2$ | 87.10 | 90.23 | 25.81 | 24.91 | 26.90 | 12.43 |
| Transportation | $tkm/m^2$ | 3.48 | 3.61 | 1.03 | 1.00 | 1.08 | 0.50 |

## 3.2 Tubular Heat Exchangers

The detailed design specifications of three tubular type HXs (preheater, evaporator and condenser) are reported in the deliverable D7.1. The important features and specifications of these tubular types HXs are listed in Table 3.7.

**Table 3.7 -** Important features and specifications of three tubular (coaxial) Heat Exchangers

| Parameters | Unit | Tubular (coaxial) Heat Exchangers | | |
|---|---|---|---|---|
| | | Preheater (PH_TU) | Evaporator (EV_TU) | Condenser (CO_TU) |
| Manufacturers | - | ACM | ACM | CM |
| Technology options | - | U-type coaxial tubes | U-type coaxial tubes | U-type coaxial tubes |
| Capacity | kW | 20 | 5 | 9.5 |
| Tube material type and grade | - | Carbon Steel : S275JR | Carbon Steel : S275JR | Carbon Steel : S275JR |
| GeoHex materials inside the tube | - | HPHP (Ni-P/Ni-P-PTFE) | HPHP (Ni-P/Ni-P-PTFE) | Tutorprom Bright materials with $SiO_2$ nanoparticles |
| GeoHex materials outside the tube | - | HST-10-150 (metal oxide nanoporous) | HSP-3.6 (Fe-doped $Al_2O_3$-$TiO_2$); | - |
| Number of tubes | - | 2 tubes in series | 2 tubes in series | 2 tubes in series |
| Length of the tube | m | 0.8 | 5 | 4 |

| | | | | |
|---|---|---|---|---|
| Inner tube outer diameter | mm | 25.4 | 13.5 | 25.4 |
| Outer tube outer diameter | mm | 42.2 | 26.7 | 42.4 |
| Thickness of the wall of the inner tube | mm | 2.11 | 2.3 | 2.11 |
| Thickness of the wall of the outer tube | mm | 3.56 | 2.87 | 3.56 |
| Heat exchange surface area | $m^2$ | 0.10 | 0.43 | 0.63 |
| Temperature range | $^0C$ | 170-120 | 170-120 | 72.5-41.5 |
| Maximum pressure* | bar | 11 | 16.45 | 7.77 |
| Overall heat transfer coefficient | $W\ m^{-2}\ K^{-1}$ | 2800 | 311 | 775 |
| Fluid types | - | Brine/water | Thermal oil/ORC fluid | ORC fluid/Water |

*on working fluid side for evaporator & condenser and on brine side for preheater.

The masses of the tube materials for 20 kW preheater, 9.5 kW condenser and 5 kW evaporator have been calculated using the respective lengths, heights and thicknesses of the respective tubes given in Table 3.7 and obtained 7.36, 36.82 and 23.21 kg, respectively. The material, transportation and energy flows in terms of functional unit of 1 $m^2$ have been calculated for three standard and three GeoHex enabled tubular type HXs (preheater, evaporator and condenser) in the construction, use and end of life phases using the data given in Tables 3.1, 3.2 and 3.7 and are listed in Tables 3.8, 3.9 and 3.10, respectively. The respective coating deposition data per $m^2$ area for three GeoHex enabled tubular type HXs have been gathered from the deliverables D5.3 and D5.4.

**Table 3.8 –** Functional mass, energy and transportation flows of 6 tubular HXs during construction phase.

| **Process name** | **Units** | **Functional Material and other flows during construction phase of 6 tubular HXs** | | | | | |
|---|---|---|---|---|---|---|---|
| | | **PH (20 kW)** | | **CO (9.5 kW)** | | **EV (5 kW)** | |
| | | **STD** | **GeoHex** | **STD** | **GeoHex** | **STD** | **GeoHex** |
| Tube material | $kg/m^2$ | 73.63 | 61.34 | 58.44 | 57.27 | 53.97 | 40.91 |
| Metal working | $kg/m^2$ | 73.63 | 61.34 | 58.44 | 57.27 | 53.97 | 40.91 |
| Transportation | $tkm/m^2$ | 14.73 | 12.27 | 11.69 | 11.45 | 10.79 | 8.18 |

**Table 3.9 -** Functional mass and transportation flows of 6 tubular HXs during use phase.

| **Process name** | **Units** | **Functional Material and other flows during use phase of 6 tubular HXs** | | | | | |
|---|---|---|---|---|---|---|---|
| | | **PH (20 kW)** | | **CO (9.5 kW)** | | **EV (5 kW)** | |
| | | **STD** | **GeoHex** | **STD** | **GeoHex** | **STD** | **GeoHex** |
| Cleaning material | $kg/m^2$ | 20 | 16.66 | 20 | 19.60 | 20 | 15.16 |
| Tap water | $litre/m^2$ | 1000 | 833 | 1000 | 980 | 1000 | 758 |
| Transportation | $tkm/m^2$ | 18.73 | 15.60 | 15.69 | 15.37 | 14.79 | 11.21 |

**Table 3.10 -** Functional energy and transportation flows of 6 tubular HXs during end of life phase.

| **Process name** | **Units** | **Functional Material and other flows during use phase of 6 tubular HXs** | | | | | |
|---|---|---|---|---|---|---|---|
| | | **PH (20 kW)** | | **CO (9.5 kW)** | | **EV (5 kW)** | |
| | | **STD** | **GeoHex** | **STD** | **GeoHex** | **STD** | **GeoHex** |
| Electrical energy | $MJ/m^2$ | 368.16 | 306.68 | 292.19 | 286.35 | 269.86 | 204.55 |
| Transportation | $tkm/m^2$ | 14.73 | 12.27 | 11.69 | 11.45 | 10.79 | 8.18 |

For all phases, background processes for material production and processing, transportation, dismantling energy, cleaning material and tap water have been gathered from ecoinvent v3.9.1 database. Table 3.11 lists ecoinvent dataset names of different materials, metal working, transportation and energy involved in all three phases.

**Table 3.11 –** ecoinvent dataset names for various materials, processes involved in all 3 phases.

| Process name | Unit | Dataset names |
|---|---|---|
| Low-alloyed steel | kg | Steel, low-alloyed, hot rolled {RER}\| production \| Cut-off, U |
| Chromium steel 18/8 | kg | Steel, chromium steel 18/8, hot rolled {RER}\| production \| Cut-off, U |
| Metal working (Low-alloyed steel product) | kg | Metal working, average for steel product manufacturing {RER}\| processing \| Cut-off, U |
| Metal working (chromium steel product) | kg | Metal working, average for chromium steel product manufacturing {RER}\| processing \| Cut-off, U |
| Road transportation | tkm | Transport, freight, lorry 16-32 metric ton, EURO6 {RER}\| transport, freight, lorry 16-32 metric ton, EURO6 \| Cut-off, U |
| Cleaning material | kg | Sodium hydroxide, without water, in 50% solution state {GLO}\| sodium hydroxide to generic market for neutralising agent \| Conseq, U |
| Water | litre | Water, harvested from rainwater {GLO}\| rainwater harvesting \| Cut-off, U |
| Electricity | MJ | Electricity, low voltage {SN}\| electricity voltage transformation from medium to low voltage \| Cut-off, U |

# 4. ENVIRONMENTAL IMPACT RESULTS

## 4.1 Plate type HXs

Using the inventoried data in Tables 3.4-3.6 and 3.11, the environmental impacts (LCIA results) for 1 m$^2$ area of 3 standard and 3 GeoHex enabled plate type HXs in three application areas (evaporator, condenser and preheater) have been evaluated using SimaPro 9.5.0.0 LCA tool considering the impact assessment methodology IMPACT 2002+ version 2.15.

The climate change (carbon footprint) networks for 1 m$^2$ area of GeoHex enabled and standard plate type evaporators are presented in Figures 4.1a and 4.1b, respectively.

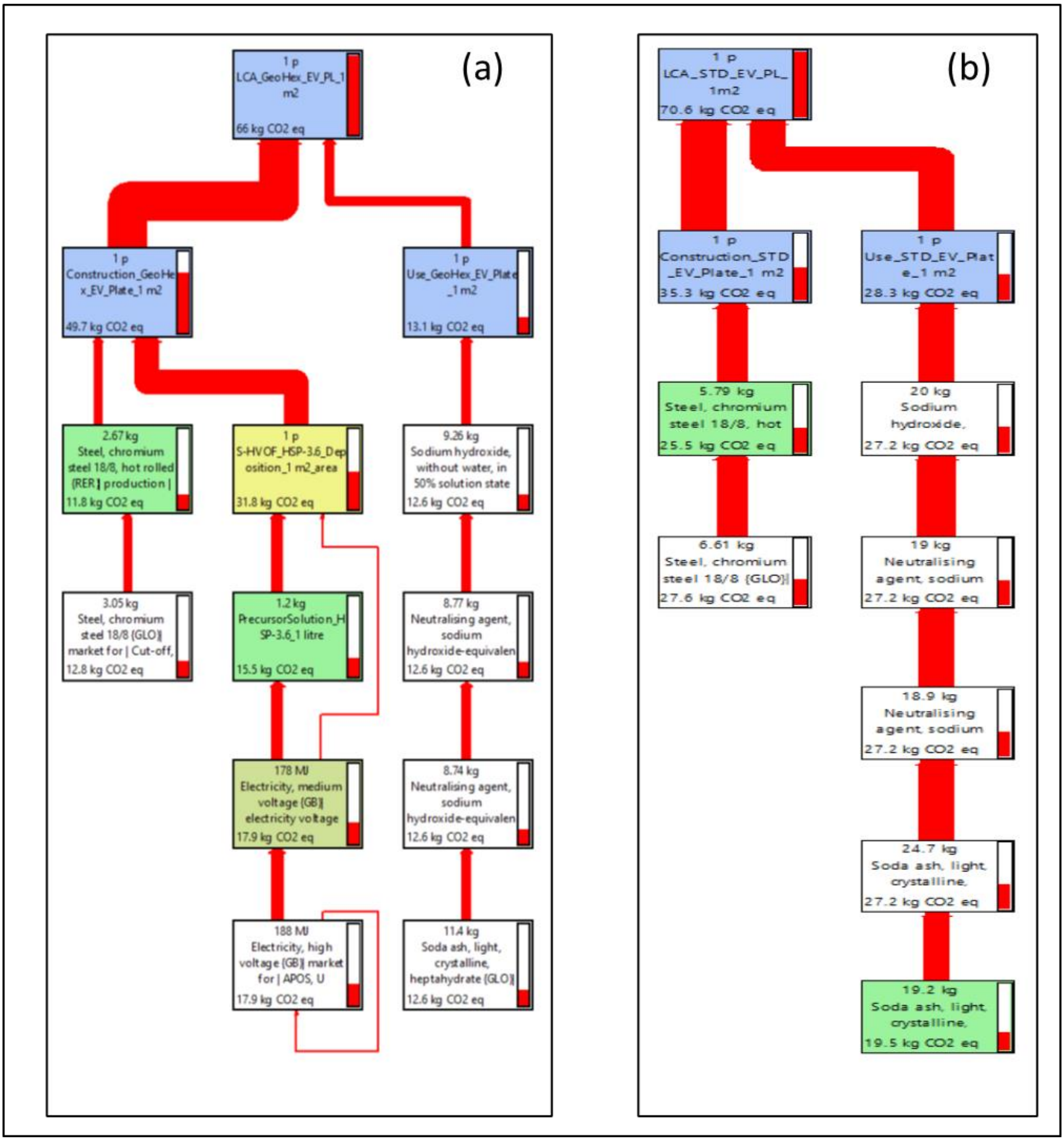


**Figure 4.1 –** A part of the climate change network models for 1 m$^2$ area of (a) GeoHex enabled and (b) standard plate type evaporators.

It is seen from Figure 4.1 that carbon footprints of GeoHex enabled and standard plate evaporators are 66 and 70.6 kg $CO_2$ eq / $m^2$, respectively. The contributions of carbon footprints in GeoHex enabled and standard plate type evaporators for construction, use & end-of-life phases are about 75%, 20% & 5% and 50%, 40% & 10%, respectively.

The climate change (carbon footprint) networks for 1 $m^2$ area of GeoHex enabled and standard plate type condensers are presented in Figures 4.2a and 4.2b, respectively.

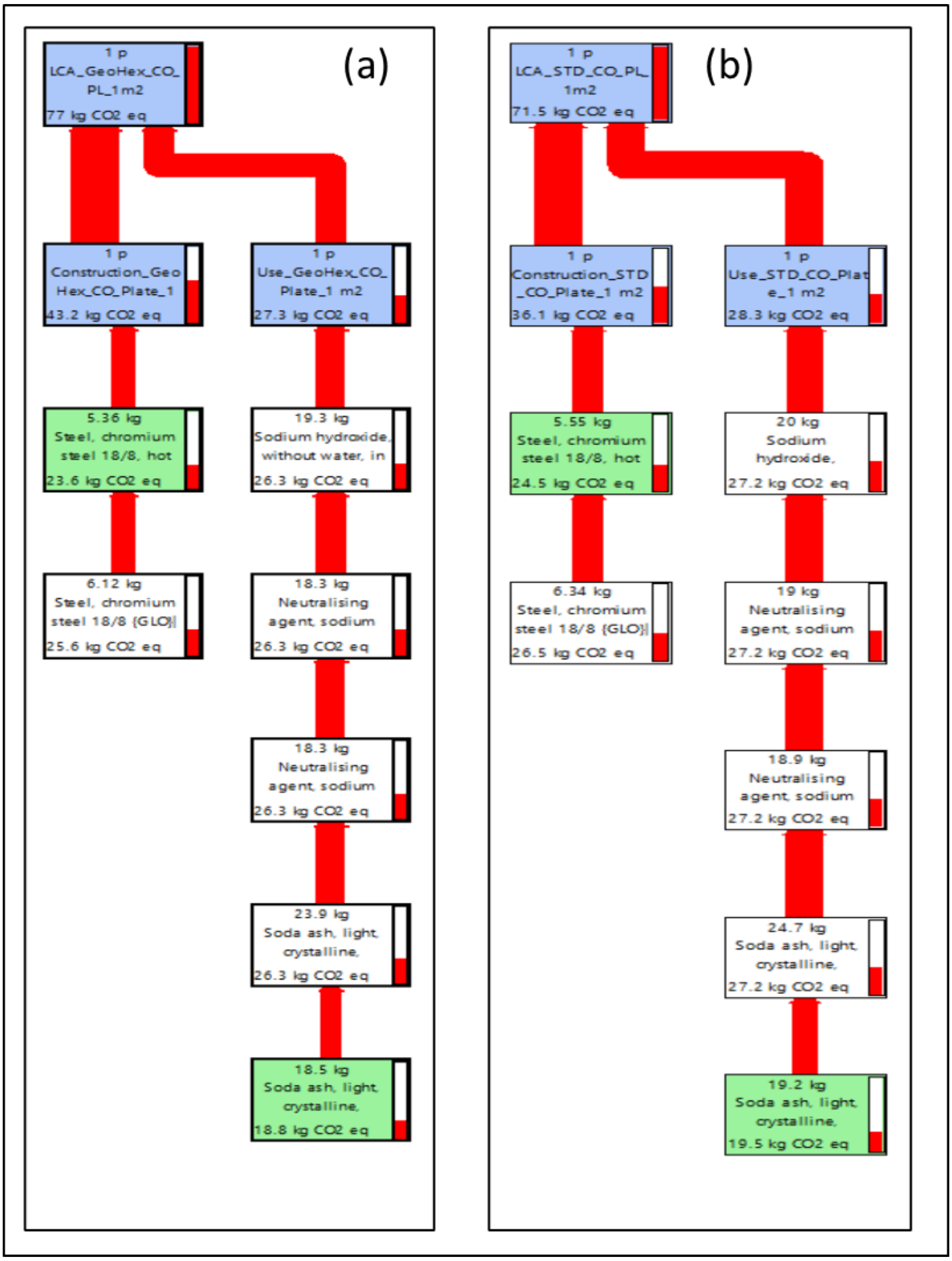


**Figure 4.2 –** A part of the climate change network models for 1 $m^2$ area of (a) GeoHex enabled and (b) standard plate type condensers.

It is seen from Figure 4.2 that carbon footprints of GeoHex enabled and standard plate condensers are 77 and 71.5 kg $CO_2$ eq / $m^2$, respectively. The contributions of carbon footprints in GeoHex enabled and standard plate type condensers for construction, use & end-of-life phases are about 56%, 35% & 9% and 50%, 40% & 10%, respectively.

The climate change (carbon footprint) networks for 1 m$^2$ area of GeoHex enabled and standard plate type preheaters are presented in Figures 4.3a and 4.3b, respectively.

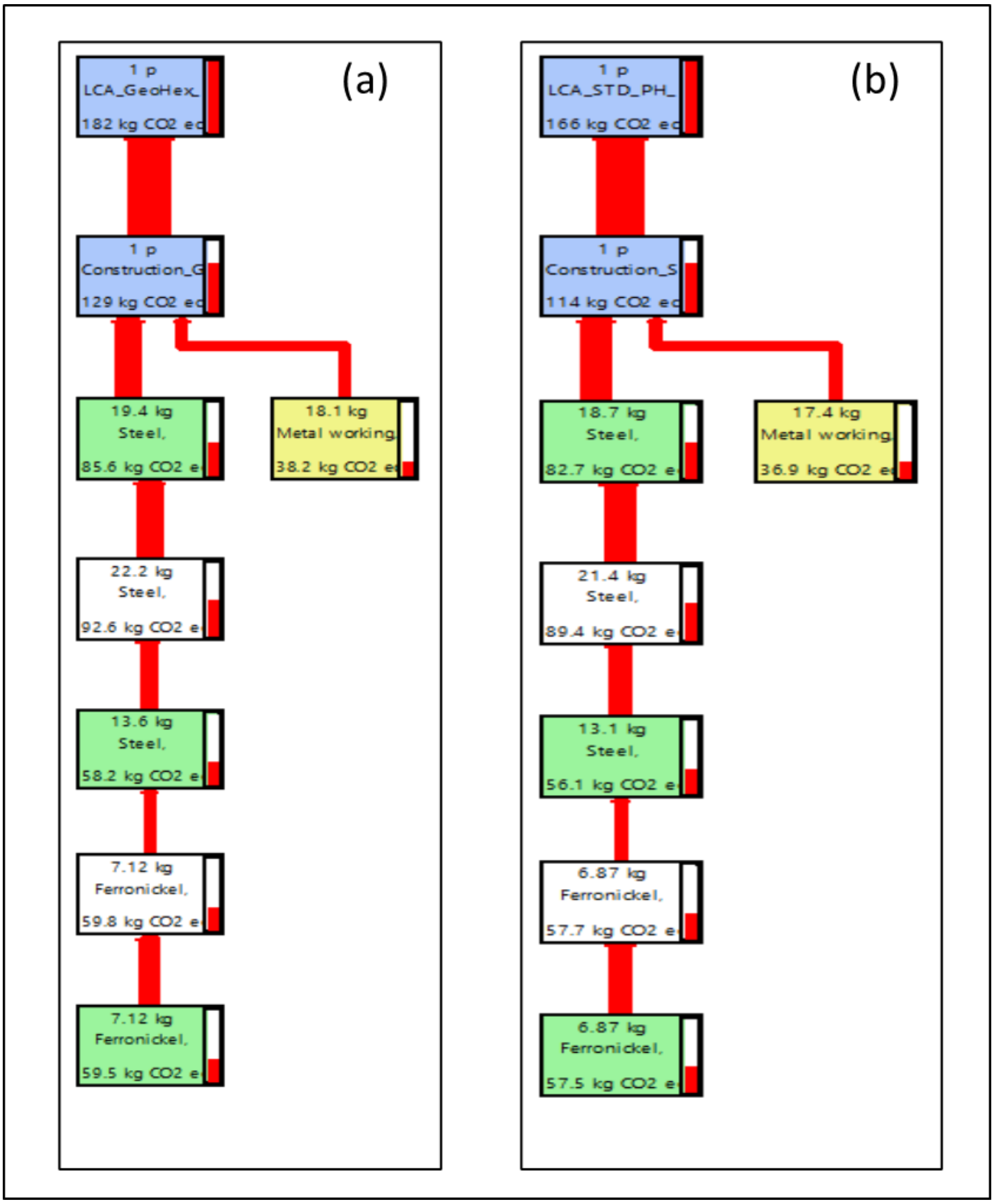


**Figure 4.3 –** A part of the climate change network models for 1 m$^2$ area of (a) GeoHex enabled and (b) standard plate type preheaters.

It is seen from Figure 4.3 that carbon footprints of GeoHex enabled and standard plate preheaters are 182 and 166 kg $CO_2$ eq / m$^2$, respectively. The contributions of carbon footprints in GeoHex enabled and standard plate type preheaters for construction, use & end-of-life phases are about 71%, 16% & 13% and 69%, 17% & 14%, respectively. It is indicated that the most of the environmental impact contributions in all 6 plate type HXs has been occurred because of the construction phase of these HXs.

The LCA tool calculated 15 mid-point impact categories for 1 $m^2$ area of 6 plate type HXs. The quantification of the LCIA results of these HXs for 15 mid-point impact categories with respective units is given in Tables 4.1.

**Table 4.1 –** Quantification of 15 midpoint impact categories for 1 $m^2$ area of 6 plate type HXs.

| Midpoint Impact Categories | Unit | CO_PL_GeoHex | CO_PL_STD | PH_PL_GeoHex | PH_PL_STD | EV_PL_GeoHex | EV_PL_STD |
|---|---|---|---|---|---|---|---|
| Carcinogens | kg C2H3Cl eq | 2.32E+00 | 2.43E+00 | 7.31E+00 | 6.77E+00 | 1.35E+00 | 2.26E+00 |
| Non-carcinogens | kg C2H3Cl eq | 3.87E+00 | 3.56E+00 | 7.85E+00 | 7.36E+00 | 2.10E+00 | 3.27E+00 |
| Respiratory inorganics | kg PM2.5 eq | 2.51E-01 | 2.55E-01 | 5.25E-01 | 4.94E-01 | 1.38E-01 | 2.52E-01 |
| Ionizing radiation | Bq C-14 eq | 3.93E+02 | -2.39E+01 | 1.25E+03 | 9.97E+02 | 2.12E+03 | 9.32E+01 |
| Ozone layer depletion | kg CFC-11 eq | 1.84E-04 | 2.72E-06 | 1.21E-05 | 1.07E-05 | 6.25E-06 | 2.97E-06 |
| Respiratory organics | kg C2H4 eq | 2.37E-02 | 2.21E-02 | 7.35E-02 | 6.37E-02 | 1.96E-02 | 2.23E-02 |
| Aquatic ecotoxicity | kg TEG water | 1.74E+04 | 2.43E+04 | 3.87E+04 | 3.64E+04 | 1.08E+04 | 1.67E+04 |
| Terrestrial ecotoxicity | kg TEG soil | 7.17E+03 | 1.01E+04 | 1.95E+04 | 1.86E+04 | 4.07E+03 | 7.31E+03 |
| Terrestrial acid/nutri | kg SO2 eq | 2.32E+00 | 2.26E+00 | 4.48E+00 | 4.11E+00 | 1.47E+00 | 2.24E+00 |
| Land occupation | m2org.arable | 7.12E+00 | 5.37E+00 | 9.72E+00 | 7.42E+00 | 7.02E+00 | 5.41E+00 |
| Aquatic acidification | kg SO2 eq | 5.89E-01 | 5.58E-01 | 1.20E+00 | 1.11E+00 | 3.79E-01 | 5.54E-01 |
| Aquatic eutrophication | kg PO4 P-lim | 3.33E-02 | 2.90E-02 | 4.63E-02 | 4.26E-02 | 1.92E-02 | 2.90E-02 |
| **Global warming** | **kg CO2 eq** | **7.70E+01** | **7.15E+01** | **1.82E+02** | **1.66E+02** | **6.60E+01** | **7.06E+01** |
| Non-renewable energy | MJ primary | 9.47E+02 | 7.73E+02 | 2.38E+03 | 2.06E+03 | 1.29E+03 | 7.86E+02 |
| Mineral extraction | MJ surplus | 2.74E+01 | 2.65E+01 | 8.58E+01 | 8.24E+01 | 1.37E+01 | 2.75E+01 |

The relative contributions of environmental footprints in GeoHex enabled and standard plate type evaporators, condensers and preheaters for 4 endpoint damage categories have been calculated with reference to the worst environmental footprint contributions considered as 100% and presented in Figure 4.4.

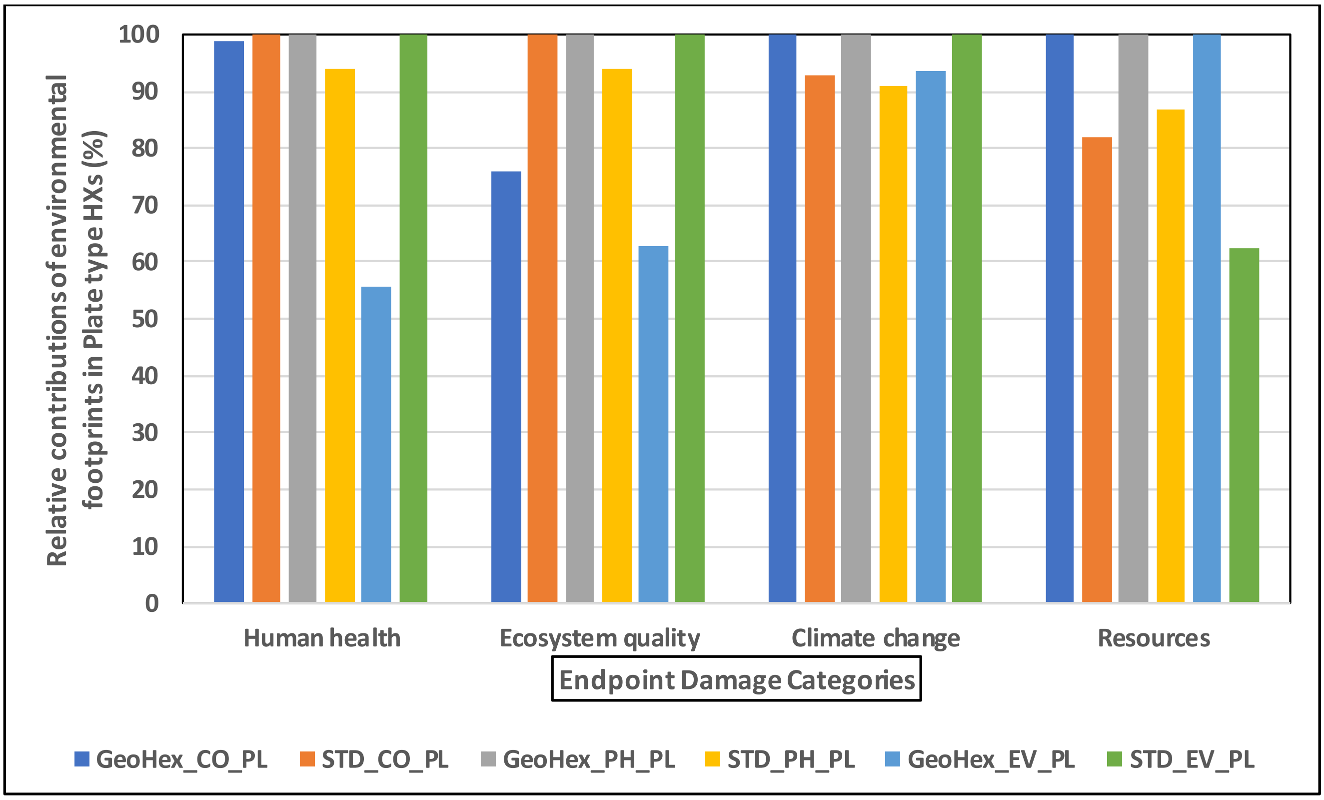


**Figure 4.4 –** Comparisons of environmental footprint contributions in 4 endpoint damage categories for 1 m$^2$ area of 6 plate type HXs.

It is evident from Table 4.1 and Figures 4.1-4.4 that the carbon footprint (climate change) savings of about +6.5%, -7.7% and -9.6% for adopting GeoHex enabled plate type evaporator, condenser and preheater, instead of using respective standard plate type HXs, respectively.

The quantified scores of four endpoint damage categories for 1 m$^2$ area of six plate type HXs in their respective units have been converted to a common scale of measurements, termed as 'single score' in units of eco-point (Pt). A graphical presentation of the total environmental footprint, along with four environmental footprints (i.e., four endpoint damage categories), in units of mPt (millipoint), of 6 plate type HXs, is shown in Figure 4.5. It is obtained that the single score values for 1 m$^2$ area of GeoHex enabled & standard plate type evaporators, condensers and preheaters are 33.38 & 44.41, 46.38 & 46.58 and 105.00 & 96.97 mPt, respectively. It is calculated that the overall environmental footprint savings are about 24.8%, 0.4% and -8.3% respectively, for adopting GeoHex enabled plate type evaporator, condenser and preheater instead of using respective plate type HXs.

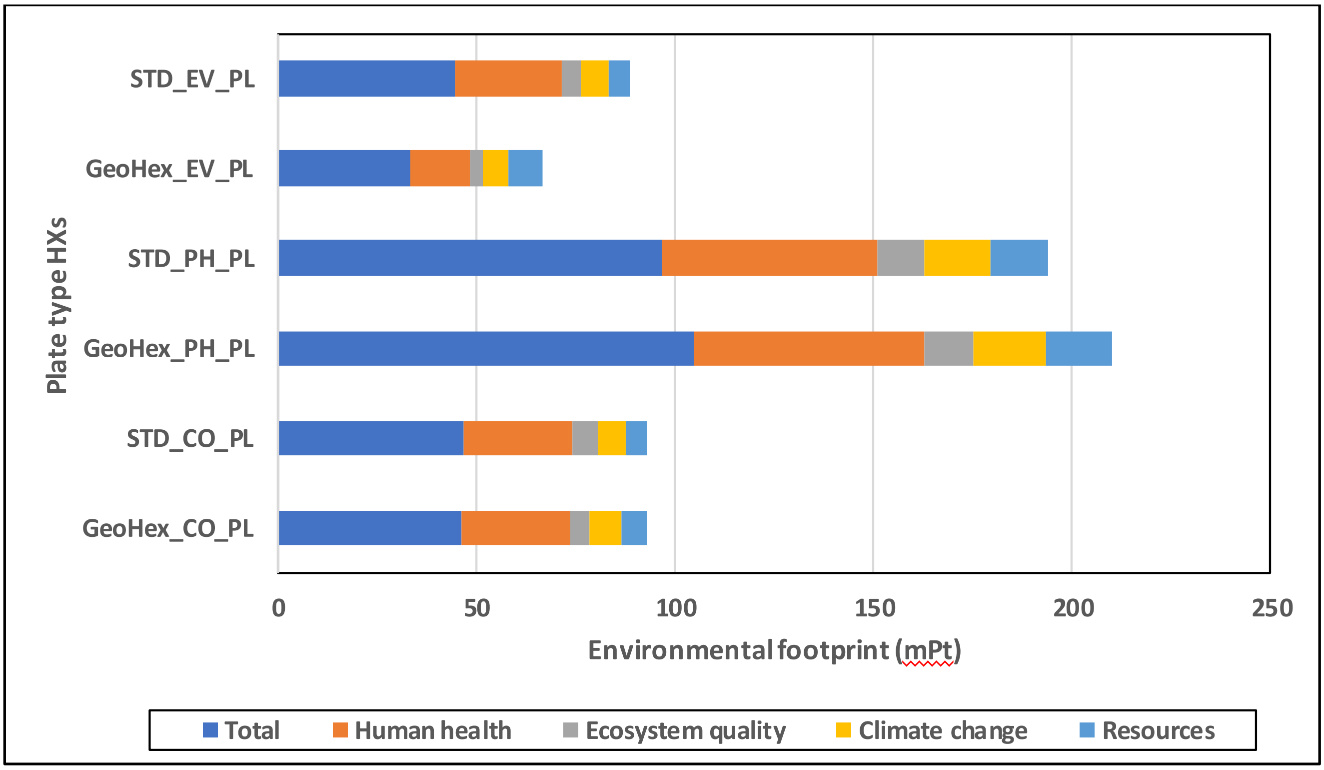


**Figure 4.5 –** Total and four environmental footprint results in mPt for 6 plate type HXs.

## 4.2 Tubular type HXs

Using the inventoried data in Tables 3.8-3.10, the environmental impacts (LCIA results) for 1 $m^2$ area of three standard and three GeoHex enabled tubular type HXs in three application areas (evaporator, condenser and preheater) have been evaluated using SimaPro 9.5.0.0 LCA tool considering the impact assessment methodology IMPACT 2002+ version 2.15.

The climate change (carbon footprint) networks for 1 $m^2$ area of GeoHex enabled and standard tubular type evaporators are presented in Figures 4.6a and 4.6b, respectively. It is seen from Figure 4.6 that carbon footprints of GeoHex enabled and standard tubular evaporators are 245 and 279 kg $CO_2$ eq / $m^2$, respectively. The contributions of carbon footprints in GeoHex enabled and standard tubular type evaporators for construction, use & end-of-life phases are about 68.5%, 9.5% & 22% and 64%, 11% & 25%, respectively.

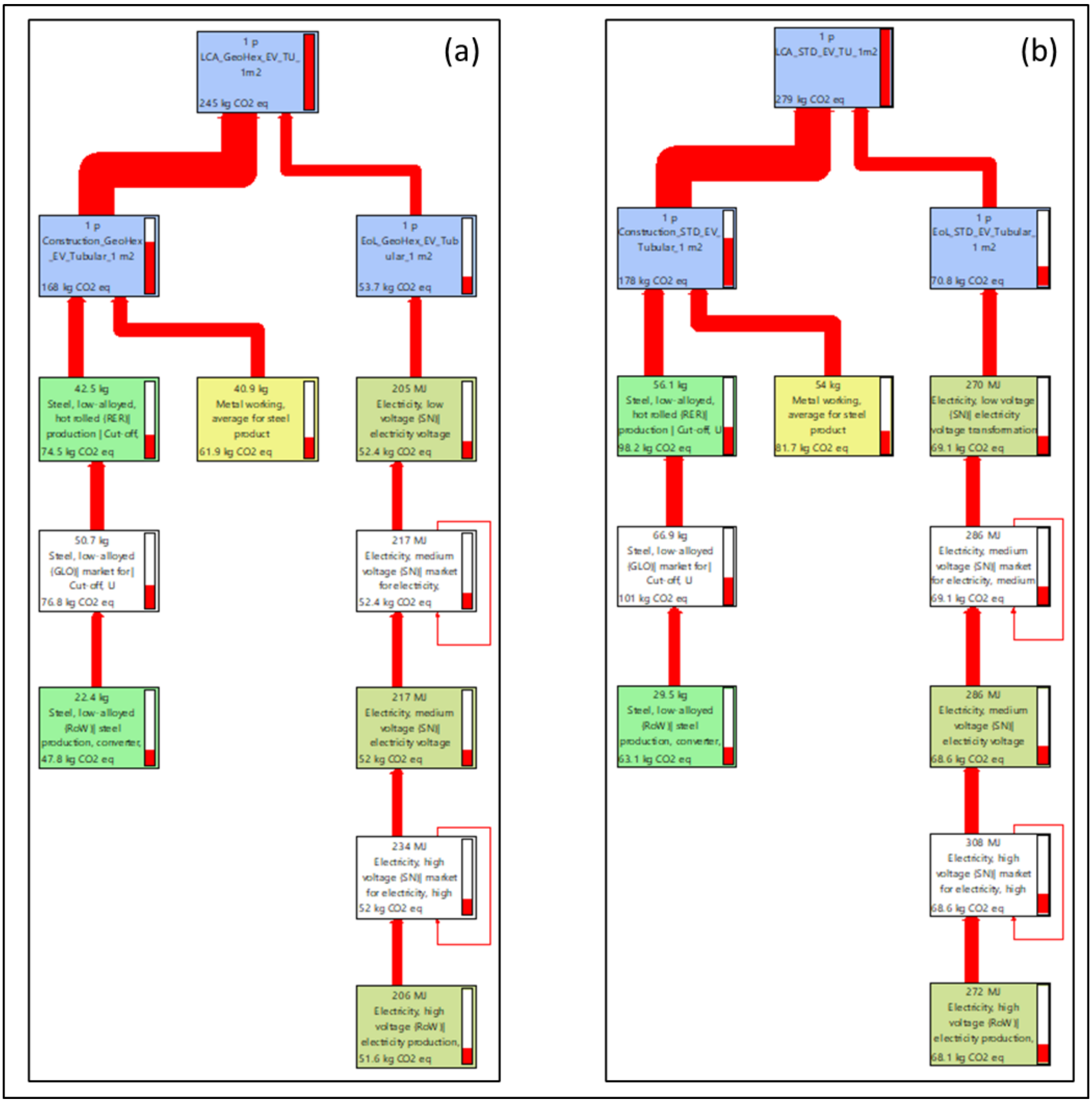


**Figure 4.6 -** A part of the climate change network models for 1 m$^2$ area of (a) GeoHex enabled and (b) standard tubular type evaporators.

The climate change (carbon footprint) networks for 1 m$^2$ area of GeoHex enabled and standard tubular type condensers are presented in Figures 4.7a and 4.7b, respectively. It is seen from Figure 4.7 that carbon footprints of GeoHex enabled and standard tubular condensers are 304 and 299 kg $CO_2$ eq / m$^2$, respectively. The contributions of carbon footprints in GeoHex enabled and standard tubular type condensers for construction, use & end-of-life phases are about 65%, 10% & 25% and 64.5%, 10.0% & 25.5%, respectively.

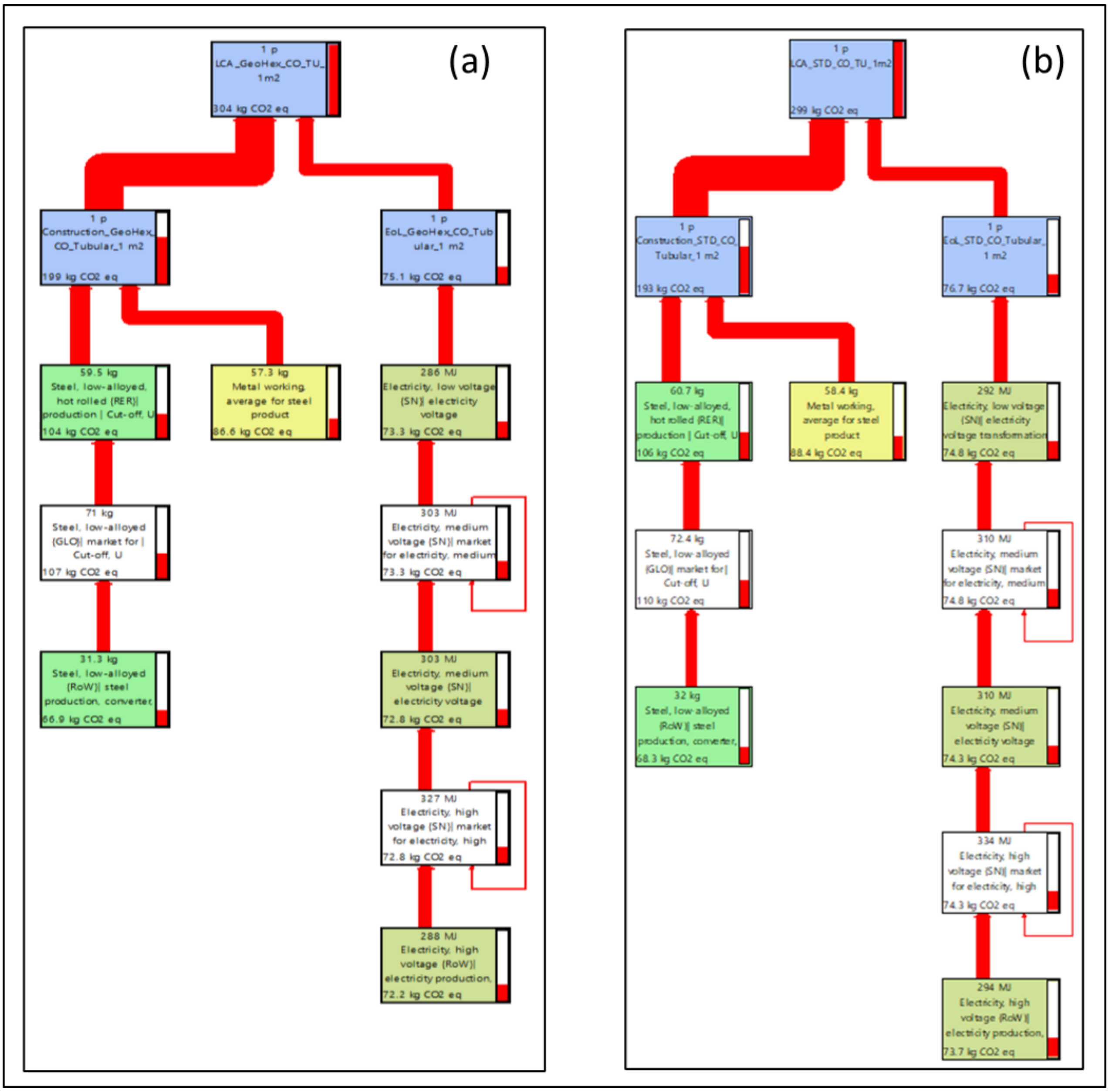


**Figure 4.7 –** A part of the climate change network models for 1 m² area of (a) GeoHex enabled and (b) standard tubular type condensers.

The climate change (carbon footprint) networks for 1 m² area of GeoHex enabled and standard tubular type preheaters are presented in Figures 4.8a and 4.8b, respectively. It is seen from Figure 4.8 that carbon footprints of GeoHex enabled and standard tubular preheaters are 320 and 370 kg $CO_2$ eq / m², respectively. The contributions of carbon footprints in GeoHex enabled and standard tubular type preheaters for construction, use & end-of-life phases are about 67%, 8% & 25% and 66%, 8% & 26%, respectively. It is demonstrated that the most of the environmental impact contributions in all 6 tubular type HXs has been occurred because of the construction phase of these HXs.

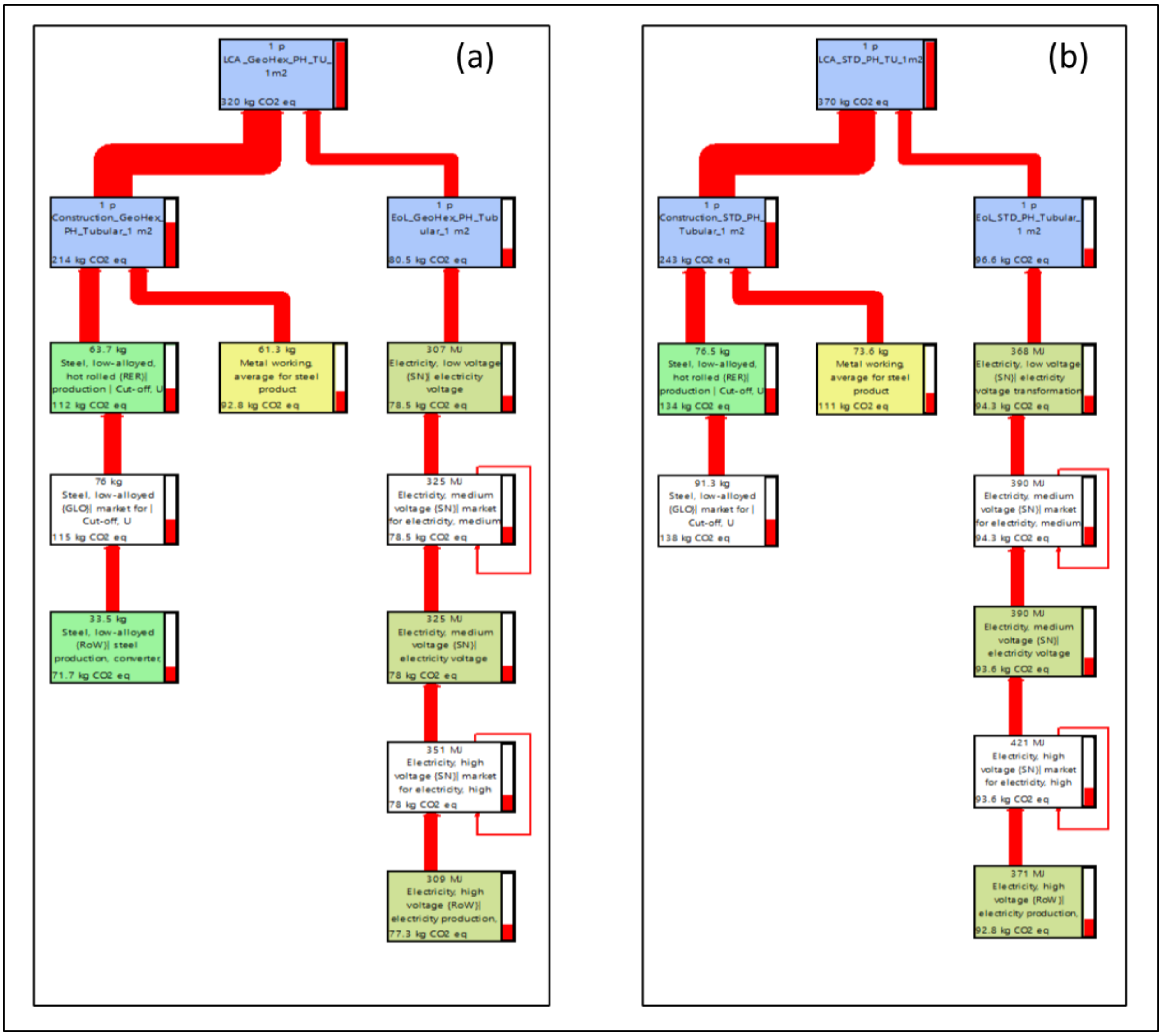

**Figure 4.8 –** A part of the climate change network models for 1 m² area of (a) GeoHex enabled and (b) standard tubular type preheaters.

The LCA tool calculated fifteenmid-point impact categories for 1 m² area of six tubular type HXs. The quantification of the LCIA results of these HXs for 15 mid-point impact categories with respective units is given in Tables 4.2.

**Table 4.2 –** Quantification of 15 midpoint impact categories for 1 m² area of 6 tubular type HXs.

| Midpoint Impact Categories | Unit | CO_TU_GeoHex | CO_TU_STD | PH_TU_GeoHex | PH_TU_STD | EV_TU_GeoHex | EV_TU_STD |
|---|---|---|---|---|---|---|---|
| Carcinogens | kg C2H3Cl eq | 1.61E+01 | 1.62E+01 | 1.70E+01 | 2.03E+01 | 1.16E+01 | 1.50E+01 |
| Non-carcinogens | kg C2H3Cl eq | 1.27E+01 | 1.22E+01 | 1.26E+01 | 1.50E+01 | 9.19E+00 | 1.13E+01 |
| Respiratory inorganics | kg PM2.5 eq | 5.28E-01 | 5.27E-01 | 5.43E-01 | 6.26E-01 | 3.99E-01 | 4.97E-01 |
| Ionizing radiation | Bq C-14 eq | 3.21E+03 | 2.95E+03 | 3.46E+03 | 3.80E+03 | 4.12E+03 | 2.70E+03 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Ozone layer depletion | kg CFC-11 eq | 2.09E-04 | 2.88E-05 | 2.70E-04 | 3.64E-05 | 2.50E-05 | 2.65E-05 |
| Respiratory organics | kg C2H4 eq | 1.79E-01 | 1.79E-01 | 1.89E-01 | 2.25E-01 | 1.35E-01 | 1.66E-01 |
| Aquatic ecotoxicity | kg TEG water | 5.90E+04 | 5.85E+04 | 6.18E+04 | 7.17E+04 | 4.45E+04 | 5.47E+04 |
| Terrestrial ecotoxicity | kg TEG soil | 1.86E+04 | 1.86E+04 | 1.95E+04 | 2.29E+04 | 1.39E+04 | 1.74E+04 |
| Terrestrial acid/nutri | kg SO2 eq | 6.43E+00 | 6.38E+00 | 6.71E+00 | 7.67E+00 | 4.98E+00 | 6.00E+00 |
| Land occupation | m2org.arable | 1.08E+01 | 8.99E+00 | 1.26E+01 | 1.02E+01 | 1.11E+01 | 8.65E+00 |
| Aquatic acidification | kg SO2 eq | 1.78E+00 | 1.76E+00 | 2.00E+00 | 2.13E+00 | 1.37E+00 | 1.65E+00 |
| Aquatic eutrophication | kg PO4 P-lim | 7.51E-02 | 7.08E-02 | 7.14E-02 | 8.33E-02 | 5.67E-02 | 6.72E-02 |
| **Global warming** | **kg CO2 eq** | **3.04E+02** | **2.99E+02** | **3.20E+02** | **3.70E+02** | **2.45E+02** | **2.79E+02** |
| Non-renewable energy | MJ primary | 4.25E+03 | 4.12E+03 | 4.42E+03 | 5.13E+03 | 3.83E+03 | 3.82E+03 |
| Mineral extraction | MJ surplus | 4.27E+01 | 4.17E+01 | 4.63E+01 | 5.17E+01 | 3.03E+01 | 3.87E+01 |

The relative contributions of environmental footprints in GeoHex enabled and standard tubular type evaporators, condensers and preheaters for 4 endpoint damage categories have been calculated with reference to the worst environmental footprint contributions considered as 100% and presented in Figure 4.9.

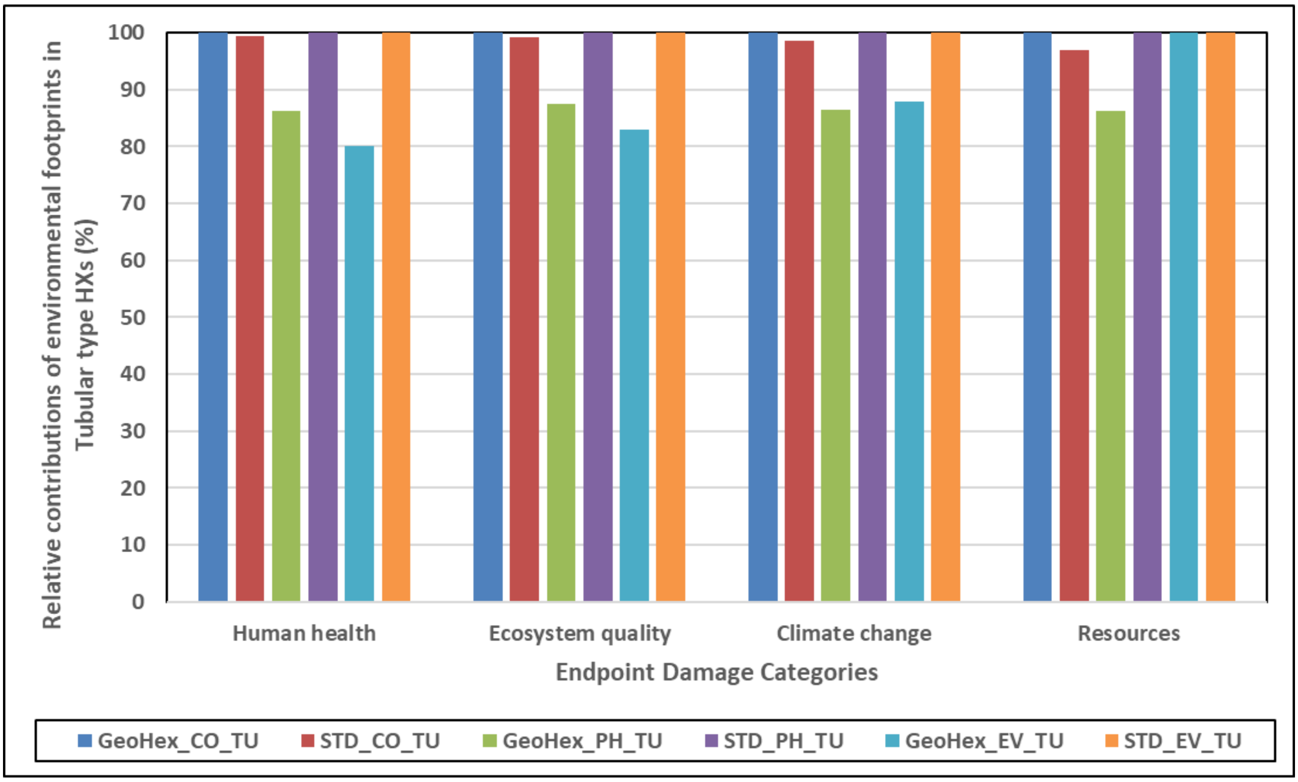


Figure 4.9 – Comparisons of environmental footprint contributions in 4 endpoint damage categories for 1 $m^2$ area of 6 tubular type HXs.

It is evident from Table 4.2 and Figures 4.6-4.9 that the carbon footprint (climate change) savings of about +12.2%, -1.7% and 13.5% for adopting GeoHex enabled tubular type evaporator, condenser and preheater, instead of using respective standard tubular type HXs are possible.

The quantified scores of four endpoint damage categories for 1 $m^2$ area ofsix tubular type HXs in their respective units have been converted to a common scale of measurements, termed as 'single score' in units of eco-point (Pt). A graphical presentation of the total environmental footprint, along with four environmental footprints (i.e., four endpoint damage categories), in units of mPt (millipoint), of 6 tubular type HXs, is shown in Figure 4.10. It is obtained that the single score values for 1 $m^2$ area of GeoHex enabled & standard tubular type evaporators, condensers and preheaters are 107.26 & 124.54, 134.90 & 133.12 and 140.24 & 162.29 mPt, respectively. It is calculated that the overall environmental footprint savings are about 13.9%, -1.3% and 13.6% respectively, for adopting GeoHex enabled plate type evaporator, condenser and preheater instead of using respective tubular type HXs.

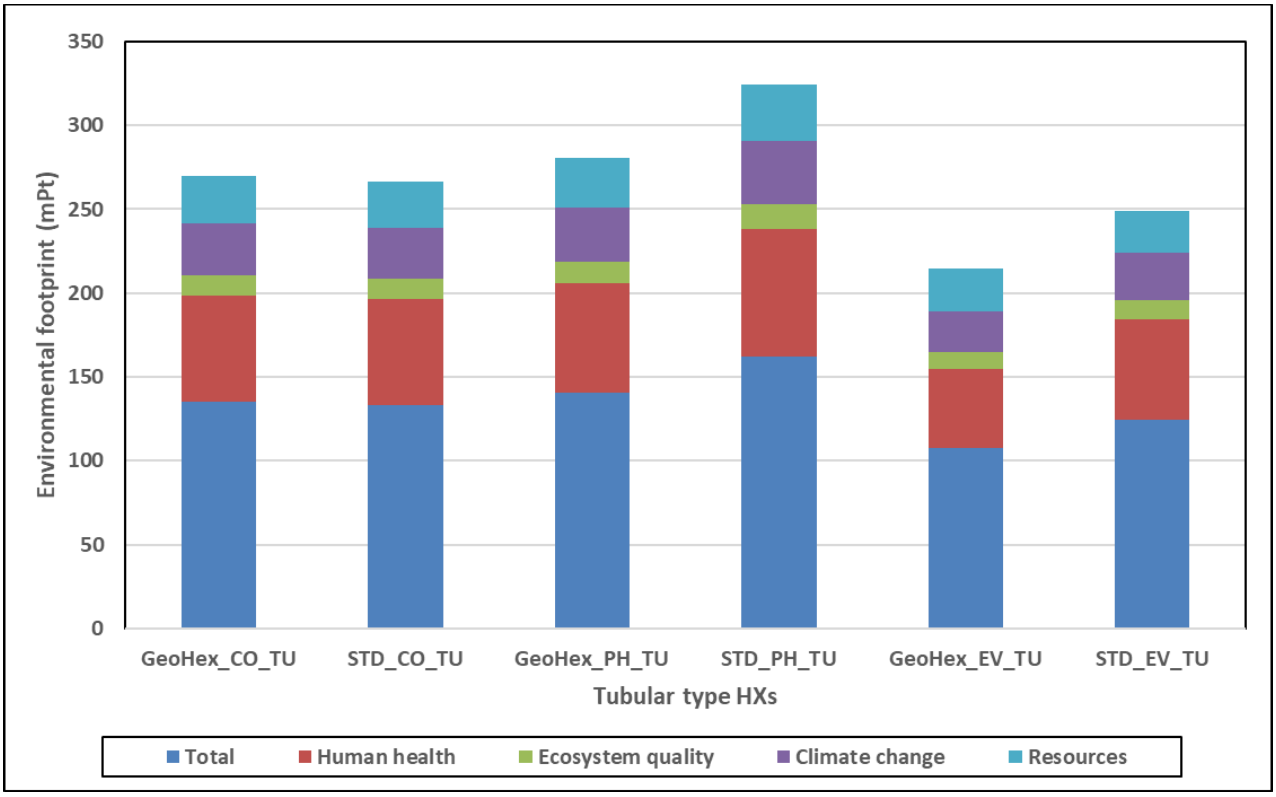


Figure 4.10 – Total and four environmental footprint results in mPt for 6 tubular type HXs.

# 5. CONCLUSIONS

The environmental impact of three tubular and three plate type HXs with and without adopting GeoHex materials have been investigated. The carbon footprint results of these HXs (standard and GeoHex enabled) were evaluated using the inventoried data in construction, use and end-of-life phases of these HXs. The respective carbon footprint savings in units of kg CO2 eq per m$^2$ area for adopting GeoHex enabled HXs have been calculated. Table 5.1 lists the quantification of carbon footprints for 1 m$^2$ area of 6 standard and 6 GeoHex enabled HXs and the carbon footprint savings for adopting three plate type and three tubular type GeoHex enabled HXs as compared with those of respective standard HXs.

**Table 5.1 –** Carbon footprint results of 12 HXs and savings for adopting GeoHex enabled HXs

| Technology options | HX types | HTC enhancement in GeoHex enabled HXs | Carbon footprint (kg CO2 eq /m$^2$) | | Carbon footprint savings | |
|---|---|---|---|---|---|---|
| | | | GeoHex enabled HXs | Standard HXs | (kg CO2 eq / m$^2$) | (%) |
| Plate | Preheater | -3.6 | 182 | 166 | -16 | -9.6 |
| | Evaporator | 53.8 | 66.0 | 70.6 | 4.6 | +6.5 |
| | Condenser | 3.5 | 77.0 | 71.5 | -5.5 | -7.7 |
| Tubular | Preheater | 16.7 | 320 | 370 | 50 | +13.5 |
| | Evaporator | 24.2 | 245 | 279 | 34 | +12.2 |
| | Condenser | 2.0 | 304 | 299 | -5 | -1.7 |

It is clearly demonstrated that the carbon footprints of GeoHex enabled evaporators in both technology options showed a lower impact as compared with respective standard HXs. This is occurred mainly due to a large increase of heat transfer coefficient in GeoHex enabled evaporators reflecting a less requirement of resource consumption. It is also demonstrated that the carbon footprint of GeoHex enabled tubular preheater showed about 13.5% lower as compared to that of standard tubular preheater. The other three GeoHex enabled HXs (plate type preheater and condenser and tubular type condenser showed higher carbon footprints as compared with the respective standard HXs.

The overall environmental footprints in units of mPt for 1 m$^2$ area of sixstandard and six GeoHex enabled HXs have calculated and the environmental footprint savings for adopting 6 GeoHex enabled HXs as compared with the respective standard HXs and these are listed in Table 5.2.

**Table 5.2 -** Environmental footprint results of 12 HXs and savings for adopting GeoHex enabled HXs

| Technology options | HX types | HTC enhancement in GeoHex enabled HXs | Environmental footprint (mPt /m$^2$) | | Environmental footprint savings | |
|---|---|---|---|---|---|---|
| | | | GeoHex enabled HXs | Standard HXs | (mPt / m$^2$) | (%) |
| Plate | Preheater | -3.6 | 105.00 | 96.97 | -8.03 | -8.3 |
| | Evaporator | 53.8 | 33.38 | 44.41 | 11.03 | +24.8 |
| | Condenser | 3.5 | 46.38 | 46.58 | 0.20 | +0.4 |
| Tubular | Preheater | 16.7 | 140.24 | 162.29 | 22.05 | +13.6 |
| | Evaporator | 24.2 | 107.26 | 124.54 | 17.28 | +13.9 |
| | Condenser | 2.0 | 134.90 | 133.12 | -1.78 | -1.3 |

It is clearly seen that the overall environmental footprint savings is about 25% for GeoHex enabled plate type evaporator as compared with that of standard plate type evaporator. The tubular types of GeoHex enabled preheater and evaporator showed about 14% savings of overall environmental footprint as compared with the respective HXs.