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D7.7 Cost performance of GeoHex enabled HXs

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Executive Summary

Cost estimation is one of the important considerations during new product development. For the evaluation of cost performances, three plate and three tubular types GeoHex enabled and standard HXs in three application areas (preheater, condenser and evaporator) have been considered. The total costs in units of € per m^2 for 6 standard HXs in two technology options have been estimated based on parametrised cost modelling. Results from these modelling studies have shown an increase in costs saving with use of GeoHex enabled HXs in comparison to standard HXs.

Objectives Met

This deliverable contributed towards the work package WP7 objective:

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

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List of Acronyms

CAPEX	CAPital EXpenditure
CO	Condenser
CS	Carbon Steel
EV	Evaporator
HTC	Heat Transfer Coefficient
HXs	Heat Exchangers
PH	Preheater
PL	Plate
SOA	State-of-the-art
SS	Stainless Steel
STD	Standard
TU	Tubular

1. INTRODUCTION

Developing an improved heat exchanger (HX) for geothermal plant is crucial to the overall product design. Some key considerations and steps in the development of a HX for a geothermal plant are as follows:

- Resource assessment: conduct a thorough assessment of geo-resources, including its temperature, pressure, flow rate and other relevant characteristics.
- Material selection: find out the materials for HXs that can withstand the specific conditions, ensuring a long operational life and preventing system failure due to corrosion and scaling damages and also can enhance the heat transfer performance.
- HX type: the selection of the technology option of the HX which best suited for the application area such as preheater, condenser and evaporator.
- Prototype testing and monitoring: It is crucial stage to validate the HX's performance under real-world conditions.
- Cost analysis: conduct a cost analysis for manufacturing/CAPEX of the improved HXs along with standard HXs.

In this study, three plate-type and three tubular-type HXs have been developed under tasks 7.1-7.3 for three application areas (preheater, condenser and evaporator), each manufactured twice. Three plate and three tubular types HXs for three application areas have been coated with respective GeoHex materials for improving the heat transfer and other performances and termed as GeoHex enabled HXs.

The other three plate and three tubular types HXs without adoption of GeoHex materials and termed as standard HXs. Table 1.1 lists six standard and six GeoHex enabled HXs in tubular and plate types with their respective capacities, material used and nomenclature.

Table 1.1 – Application area, technology option and capacities of 6 standard and 6 GeoHex enabled HXs

HX category	Technology option	Application area	Thermal capacity (kW)	Material type and grade	HX ID
Standard (STD)	Tubular (TU)	Preheater (PH)	20	CS: S275JR	PH_TU_STD
		Condenser (CO)	9.5		CO_TU_STD
		Evaporator (EV)	5		EV_TU_STD
	Plate (PL)	Preheater	60	SS:316L	PH_PL_STD
		Condenser	53		CO_PL_STD
		Evaporator	45		EV_PL_STD
GeoHex enabled (GeoHex)	Tubular	Preheater	20	CS: S275JR	PH_TU_GeoHex
		Condenser	9.5		CO_TU_GeoHex
		Evaporator	5		EV_TU_GeoHex
	Plate	Preheater	60	SS:316L	PH_PL_GeoHex
		Condenser	53		CO_PL_GeoHex
		Evaporator	45		EV_PL_GeoHex

The goal of this study is to estimate the total costs of all six standard HXs based on parametrised cost modelling, and to determine and analyse the total costs of 6 GeoHex enabled HXs considering the respective enhancement or degradation of the heat transfer performance as compared to the respective six standard HXs and the respective coating deposition cost. The functional unit of this cost analysis study is considered as € per m^2 heat exchanged surface area of these HXs.

Section 2 describes the design specifications of three plate and three tubular type HXs. The parametrised cost modelling, deductions of parametrised costing equations, and estimated total costs of three plate and three tubular types HXs are given in section 3. In section 4, the cost performances of three plate and three tubular types GeoHex enabled and standard HXs are analysed. The main important findings of these HXs' costing are described in section 5.

2. STANDARD AND GEOHEX ENABLED HEAT EXCHANGERS

For demonstration purposes, three plate and three tubular types of heat exchangers (HXs) have been designed for three application areas (preheater, evaporator and condenser) each manufactured twice and their plate and tube materials made with stainless steel materials (316L) and carbon steel (S275JR), respectively. Three plate and three tubular types HXs without adoption of GeoHex materials termed as Standard (STD) HXs and the other three plate and three tubular types HXs with adoption of GeoHex materials into their plates and tubes' heat exchanged surface area termed as GeoHex enabled (GeoHex) HXs.

2.1 Plate Heat Exchangers

The plate type HXs in evaporator and condenser application areas have been manufactured by Alfa Laval and the plate type HXs in preheater application area have been manufactured by Nexson. These six plate type HXs are 'off-the-shelf' products. Three plate type HXs (preheater, evaporator, condenser) are not coated and considered as standard plate type HXs and identified as PH_PL_STD, EV_PL_STD and CO_PL_STD. The other three plate type HXs (preheater, evaporator, condenser) are coated with the best GeoHex coating materials and considered as GeoHex enabled plate type HXs and identified as PH_PL_GeoHex, EV_PL_GeoHex and CO_PL_GeoHex. The heat capacities of plate type preheater, evaporator and condenser are 60 kW, 45 kW and 53 kW, respectively. The detailed design specifications of these three plate type HXs are reported in the deliverable D7.1.

2.2 Tubular Heat Exchangers

Six tubular type HXs in preheater, evaporator and condenser application areas have been manufactured by ACM. These six tubular type HXs are 'tailor-made' products. Three tubular type HXs (preheater, evaporator, condenser) are not coated and considered as standard tubular type HXs and identified as PH_TU_STD, EV_TU_STD and CO_TU_STD. The other three tubular type HXs (preheater, evaporator, condenser) are coated with the best GeoHex coating materials and considered as GeoHex enabled tubular type HXs and identified as PH_TU_GeoHex, EV_TU_GeoHex and CO_TU_GeoHex. The heat capacities of tubular type preheater, evaporator and condenser are 20 kW, 5 kW and 9.5 kW, respectively. The detailed design specifications of these three tubular types HXs are reported in the deliverable D7.1.

3. COST MODELLING

3.1 Parametrised Cost Modelling Framework

In this study, three plate and three tubular types of heat exchangers (HXs) have been developed for three application areas: preheater, evaporator and condenser. For estimation of the CAPEX of these six HXs, the parametrised cost modelling approach has been considered. The CAPEX of each HX has been evaluated based on parametrised cost modelling. For each HX, CAPEX comprising the following cost components:

- Material cost ($Cost^{material}$)
- Manufacturing cost ($Cost^{manufact}$)
- Overhead ($Cost^{overhead}$)
- Profit ($Cost^{profit}$)

Therefore, we have, CAPEX for a particular HX,

$$\text{CAPEX} = Cost^{material} + Cost^{manufact} + Cost^{overhead} + Cost^{profit} \tag{3.1}$$

Where, $Cost^{material}$ = purchasing cost of raw materials including labour and transportation;

$Cost^{manufact}$ = manufacturing factor x Material cost = $f_m \bullet Cost^{material}$; here, f_m is generally considered to be 2 to 4. It includes the labour and electrical energy cost along with others (e.g., machining, engineering, assembling, etc.).

$Cost^{overhead}$ = *overhead factor* x Manufacturing cost = $f_o \bullet Cost^{manufact}$; here, f_o is usually includes items such as services, insurance, taxes, facilities maintenance, and the depreciation of the equipment. It is usually 0.2 to 0.5.

$Cost^{profit}$ = *profit factor* * Manufacturing cost = $f_p \bullet Cost^{manufact}$; here, f_p is generally considered to be 0.2 to 0.4.

The parametrised costing equations of the material cost, manufacturing cost, overhead and profit components for tubular coaxial and plate & gasketed HXs have been deduced in subsections 3.2.1 and 3.2.2, respectively. The estimated CAPEX of these six HXs have been calculated based on parametric costing equations using average unit costs of the material and the approximate values of different factors involved and presented in the section 3.3.

3.2 Parametrised Costing Equations

3.2.1 Tubular Coaxial HXs

The total material cost for a particular tubular coaxial HX (either 20 kW preheater, or 5 kW evaporator or 9.5 kW condenser) made with standard material is calculated using the four cost sub-components and given by

Material cost = Inner tube material cost + Outer tube material cost + Insulation material cost + Aluminium material cost

$$Cost^{material} = T_{cost,\,inner} + T_{cost,\,outer} + I_{cost} + Al_{cost} \tag{3.2}$$

The parametrised costing equations for four cost sub-components (inner tube, outer tube, insulation and aluminium) have been deduced as follows:

Inner Tube material cost in € ($T_{cost,\,inner}$) = volume of the material of the inner tube (m^3) x density (kg m^{-3}) x mass multiplication factor x unit cost of tube material (€/kg)

Here, volume of the material of the inner tube = $N_t \left(\frac{\pi D_o^{i,2}}{4} - \frac{\pi D_i^{i,2}}{4}\right) L_i$; where, D_o^i, D_i^i *and* L_i *are the outer & inner diameters and length of the inner tube, respectively;* N_t *= total number of tubes in series*

Therefore, we have,

$$T_{cost,\,inner}\,(€) = N_t \left(\frac{\pi D_o^{i,2}}{4} - \frac{\pi D_i^{i,2}}{4}\right) L_i\, \rho_t\, f_{mm}\, U_{tm} \tag{3.3}$$

Here, $D_i^i = (D_o^i - 2t_i)$; *t_i is the thickness of the inner tube;* ρ_t *= density of the tube material and* U_{tm} *= Unit cost of the tube material* (€/kg), f_{mm} *= mass multiplication factor, which is usually considered to be 1.2.*

Outer Tube material cost in € ($T_{cost,\ outer}$) = volume of the material of the outer tube (m^3) x density (kg m^{-3}) x mass multiplication factor x unit cost of tube material (€/kg)

Here, volume of the material of the outer tube = $N_t\ (\frac{\pi D_o^{o,2}}{4} - \frac{\pi D_i^{o,2}}{4})\ L_{o;}$ where, D_o^o, D_i^o *and* L_o *are the outer & inner diameters and length of the outer tube, respectively.*

Therefore, we have,

$$T_{cost,\ \mathrm{outer}}\ (€) = N_t\ (\frac{\pi D_o^{o,2}}{4} - \frac{\pi D_i^{o,2}}{4})\ L_o\, \rho_t\, f_{mm}\, U_{tm} \qquad (3.4)$$

Here, $D_i^o = (D_o^o - 2t_o)$; *t_o is the thickness of the outer tube;* ρ_t *= density of the tube material and* U_{tm} *= Unit cost of the tube material* (€/kg), f_{mm} *= mass multiplication factor, which is usually considered to be 1.2.*

Insulation material cost in € (I_{cost}) = volume (m^3) of the insulating material x density (kg m^{-3}) x material wastage factor x unit cost of insulating material (€/kg)

Here, volume of the insulating material = total surface area x thickness of the insulating material

= (surface area of the outer wall of the outer tube + surface area of the inner wall of the outer tube) x thickness of the insulating material.

Therefore, we have,

$$I_{cost}\ (€) = (\pi\ D_o^o\ L_o + \pi\ D_i^o\ L_o)\ t_{im}\, \rho_{im}\, f_{mm}\, U_{im} \qquad (3.5)$$

Here, t_{im} *= thickness of the insulating material,* ρ_{im} *= density of the insulating material,* U_{im} *= unit cost of insulating material* (€/kg).

Aluminium material cost in € (Al_{cost}) = Volume of the Aluminium material (m^3) x density (kg m^{-3}) x Unit cost of Aluminium material (€/kg).

Here, volume of the aluminium material = total surface area x thickness of the aluminium material

= (surface area of the outer wall of the outer tube + surface area of the inner wall of the outer tube) x thickness of the aluminium material.

Therefore, we have,

$$Al_{cost}\ (€) = (\pi\ D_o^o\ L_o + \pi\ D_i^o\ L_o)\ t_{Al}\, \rho_{Al}\, f_{mm}\, U_{Al} \qquad (3.6)$$

Here, t_{Al} *= thickness of the aluminium material,* ρ_{Al} *= density of the aluminium material,* U_{Al} *= unit cost of aluminium material* (€/kg).

Material cost and CAPEX estimation

Combining the equations (3.2) – (3.6), the total material cost for a standard tubular HX is given by

$$Cost^{material}\ (€) = N_t\ (\frac{\pi D_o^{i,2}}{4} - \frac{\pi D_i^{i,2}}{4})\ L_i\, \rho_t\, f_{mm}\, U_{tm} + N_t\ (\frac{\pi D_o^{o,2}}{4} - \frac{\pi D_i^{o,2}}{4})\ L_o\, \rho_t\, f_{mm}\, U_{tm} + (\pi\ D_o^o\ L_o + \pi\ D_i^o\ L_o)\ t_{im}\, \rho_{im}\, f_{mm} + (\pi\ D_o^o\ L_o + \pi\ D_i^o\ L_o)\ t_{Al}\, \rho_{Al}\, f_{mm}\, U_{Al} \qquad (3.7)$$

Finally, using equations (3.1) and (3.7), The CAPEX of a particular tubular coaxial type HX (preheater, or evaporator, or, condenser) module made with the carbon steel material in € can be estimated.

3.2.2 Plate & Gasketed HXs

The total material cost for a particular plate & gasketed HX (either 60 kW preheater, or 45 kW evaporator or 53 kW condenser) made with standard material is calculated using the four cost sub-components and given by

Material cost = plate material cost + front & end cover material cost + support rod material cost + gasketed material cost

$$Cost^{material} = M_{cost,\ plate} + M_{cost,\ cover} + M_{cost,\ support} + M_{cost,\ gasketed} \qquad (3.8)$$

The parametrised costing equations for four cost sub-components (plate, front & end cover, support rod and gasket) have been deduced as follows:

Plate material cost in € ($M_{cost,\ plate}$) = total volume of the material of the plate (m^3) x density ($kg\ m^{-3}$) of the plate material x mass multiplication factor x unit cost of plate material (€/kg).

Here, total volume of the material of the plate = $N_p\ L_p\ H_p\ t_p$

Where, L_p, H_p and t_p are the length, height and thickness of the plate, respectively; N_p = total number of plates.

Therefore, we have,

$$M_{cost,\ plate}\ (€) = N_p\ L_p\ H_p\ t_p\ \rho_p f_{mm}\ U_{pm} \quad (3.9)$$

Front & end cover material cost *in € ($M_{cost,\ cover}$)* = total volume of the front & end cover material (m^3) x density ($kg\ m^{-3}$) of the cover material x mass multiplication factor x unit cost of cover material (€/kg)

Here, total volume of the cover material = $N_c\ L_c\ H_c\ t_c$

Where, L_c, H_c and t_c are the length, height and thickness of the cover material, respectively; N_c = total number of cover sheet.

Therefore, we have,

$$M_{cost,\ cover}\ (€) = N_c\ L_c\ H_c\ t_c\ \rho_c f_{mm}\ U_{cm} \quad (3.10)$$

Support rod material cost *in € ($M_{cost,\ support}$)* = total volume of the support rod material (m^3) x density ($kg\ m^{-3}$) of the support material x mass multiplication factor x unit cost of support material (€/kg)

Here, total volume of the support material = $N_s \frac{\pi\ {D_s}^2}{4} L_s$

L_s and D_s are the length and diameter of the support rod material, respectively; N_s = total number of support rod.

Therefore, we have,

$$M_{cost,\ support}\ (€) = N_s \frac{\pi\ {D_s}^2}{4} L_s\ \rho_s f_{mm}\ U_{sm} \quad (3.11)$$

Gasketed material cost *in € ($M_{cost,\ gasketed}$)* = total number of plates x unit cost of gasketed material (€/pc)

Therefore, we have,

$$M_{cost,\ gasketed}\ (€) = N_p\ U_{gm} \quad (3.12)$$

Combining the equations (3.8) – (3.12), the total material cost for a plate HX is given by

$$Cost^{material} = N_p\ L_p\ H_p\ t_p\ \rho_p f_{mm}\ U_{pm} + N_c\ L_c\ H_c\ t_c\ \rho_c f_{mm}\ U_{cm} + N_s \frac{\pi\ {D_s}^2}{4} L_s\ \rho_s\ f_{mm}\ U_{sm} + N_p\ U_{gm} \quad (3.13)$$

Finally, using equations (3.1) and (3.13), The CAPEX of a particular plate & gasketed type HX (preheater, or evaporator, or, condenser) module made with the stainless steel material in € can be estimated.

3.3 Estimated CAPEX of HXs

Based on the design specifications of HXs, CAPEX of three tubular and three plate types HXs made with carbon and stainless steel materials have been estimated using the respective parametrised costing equations and given in Table 3.1 along with

- the purchasing costs ('off-the shelf' for plate HXs and 'tailor-made' for tubular HXs) of these HXs provided by CEA and
- the approximated costs of three shell & tube HXs have been calculated using the deduced equation in the reference (Jaric et al., 2019).

Table 3.1 - Estimated CAPEX, approximated and purchasing costs for 3 Tubular and 3 Plate type HXs

Application area	Design options	Tube or plate material	Thermal capacity (kW)	Heat exchanged surface area (m^2)	Estimated CAPEX of HXs (cost modelling) (€)	Approx. costs of shell & tube HXs[2] (€)	Purchasing cost of tailor-made or off-the-shelf HXs[3] (€)
Preheater	Plate	SS	60	0.6	1118		1130**
	Tubular	CS	20	0.1	110	140	9850*
Evaporator	Plate	SS	45	4.3	2412		2510**
	Tubular	CS	5	0.43	340	360	9965*
Condenser	Plate	SS	53	3.3	1702		1600**
	Tubular	CS	9.5	0.63	530	460	9965*

*'tailor-made' products; **'Off-the-shelf' products.

It is evident from Table 3.1 that:

- The purchasing costs of three 'off-the-shelf' plate type HXs are in good agreement with the estimated CAPEX of the respective plate type HXs using parametric cost modelling.
- The purchasing costs of three 'tailor-made' tubular type HXs do not comply with the estimated CAPEX of the respective tubular type HXs due to 'tailor-made' products.
- The approximated costs of three shell & tube type HXs are similar to the respective estimated CAPEX of three tubular type HXs.

For cost performance analysis of those HXs with and without adoption of GeoHex materials, the estimated CAPEX of all these six HXs based on parametrised cost modelling has been considered. The estimated CAPEX of these six HXs per m^2 heat exchanged area has been calculated using the respective estimated CAPEX of HXs from Table 3.1 and listed in Table 3.2.

Table 3.2 – Estimated CAPEX of six HXs per unit area

Application area	Technology options	Heat exchanged surface area (m^2)	Estimated CAPEX of HXs per unit area (€/m^2)	HX ID
Preheater (PH)	Plate (PL)	1	1863	PH_PL_STD_1m2
	Tubular (TU)		1064	PH_TU_STD_1m2
Evaporator (EV)	Plate (PL)		561	EV_PL_STD_1m2
	Tubular (TU)		780	EV_TU_STD_1m2
Condenser (CO)	Plate (PL)		516	CO_PL_STD_1m2
	Tubular (TU)		844	CO_TU_STD_1m2

[2] Jarić, M. S., *et al.*: 'Total costs of shell and tube heat exchangers with concentric helical tube coils; Thermal Science, 2019, Vol. 23 No. 6A, pp. 3661-3673.

[3] Personal communication, GeoHex consortium partner CEA, February 2023.

4. COST PERFORMANCE RESULTS

4.1 Plate type HXs

For cost analysis of three plate type HXs with and without adoption of GeoHex materials, the estimated costs of these HXs have been considered. Manufacturers produced each HX twice for three application areas (preheater, evaporator, and condenser), ones for without adoption of GeoHex materials and considered as standard (STD) HXs and the other three ones are coated with the respective GeoHex materials and considered as GeoHex enabled (GeoHex) HXs, i.e., with the adoption of the respective GeoHex materials. To obtain the CAPEX of 3 GeoHex enabled plate type HXs (preheater, condenser and evaporator), the respective coating deposition cost are added to the respective estimated CAPEX of 3 standard plate type HXs. Table 4.1 lists the CAPEX of 3 standard and 3 GeoHex enabled plate type HXs in units of €/m^2.

Table 4.1 – CAPEX of 3 standard and GeoHex enabled plate type HXs

Application area	Thermal capacity	Heat exchanged area	CAPEX of plate type HXs (€/m^2)	
	(kW)	(m^2)	STD	GeoHex
Preheater	60	0.6	1863	2219
Condenser	53	3.3	516	709
Evaporator	45	4.3	561	634

The heat transfer performance of these six plate type HXs have been measured in mini ORC plant at CEA facilities and the results of overall heat transfer coefficient (HTC) of these HXs have been obtained from CEA and given in Table 4.2.

Table 4.2 – Overall HTC results of plate HXs and CAPEX of 3 GeoHex enabled plate HXs.

Application area	Overall HTC results of plate type HXs (W m^{-2} K^{-1})		Enhancement or degradation of HTC for adopting GeoHex materials	CAPEX of GeoHex enabled plate HXs considering the impacts of heat transfer performance results
	STD	GeoHex	(%)	(€/m^2)
Preheater	4200	4050	-3.6	2301
Condenser	2029	2100	+3.5	685
Evaporator	394	606	+53.8	412

Based on the enhancement of HTC in GeoHex enabled HXs, the CAPEX of GeoHex enabled HXs per m^2 area have been calculated and obtained € 2301, € 685 and € 412 per m^2 area for GeoHex enabled plate type preheater, condenser and evaporator, respectively. The relative CAPEX costs of these three GeoHex enabled and the respective standard HXs are depicted in Figure 4.1. It is obtained that for adopting GeoHex enabled plate type evaporator instead of using the standard plate type evaporator showed about 27% cost savings. But GeoHex enabled plate type condenser and preheater showed about 25% and 19% higher costs than those of respective standard HXs.

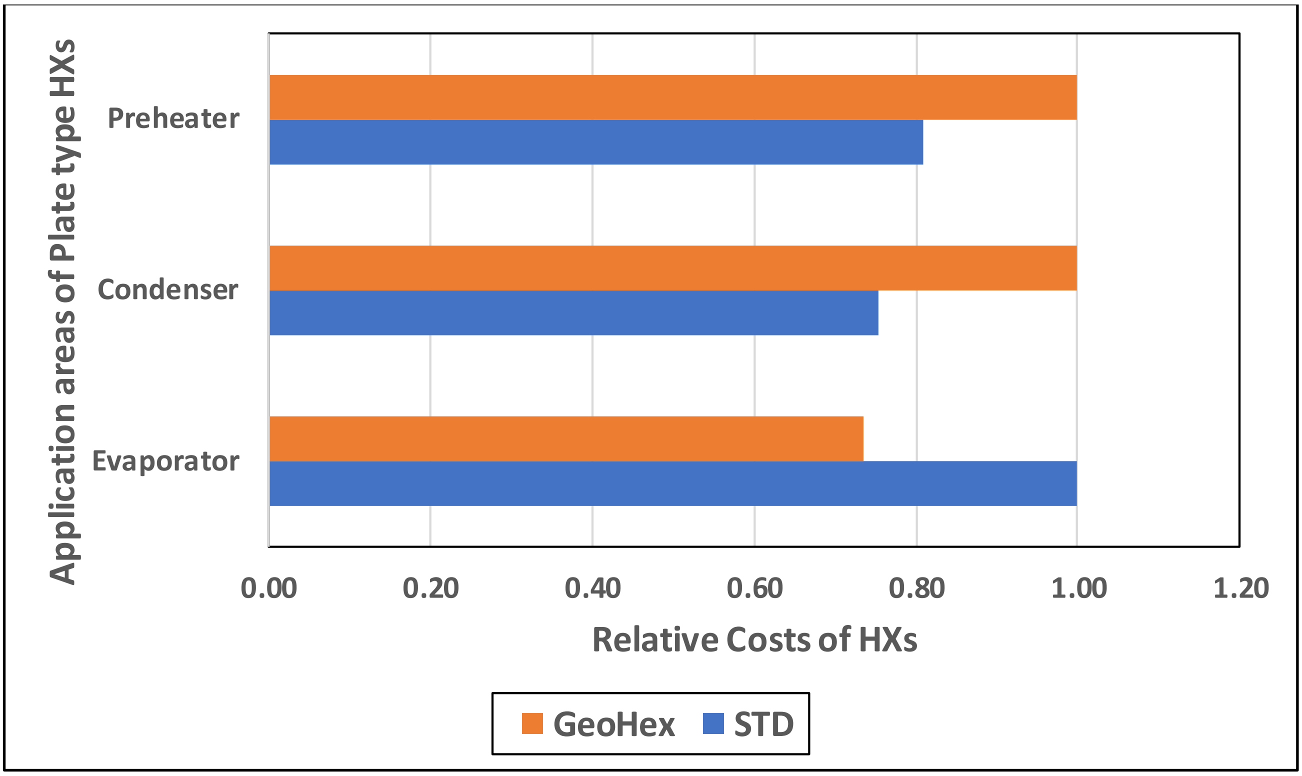

Figure 4.1 – Relative costs of three GeoHex enabled and respective standard plate type HXs.

The cost savings per m^2 area of these three plate type preheater, condenser and evaporator have also been calculated for adopting GeoHex enabled HXs instead of using the respective standard HXs. Figure 4.2 shows the cost savings in percentage of GeoHex enabled plate type HXs instead of using the respective standard HXs.

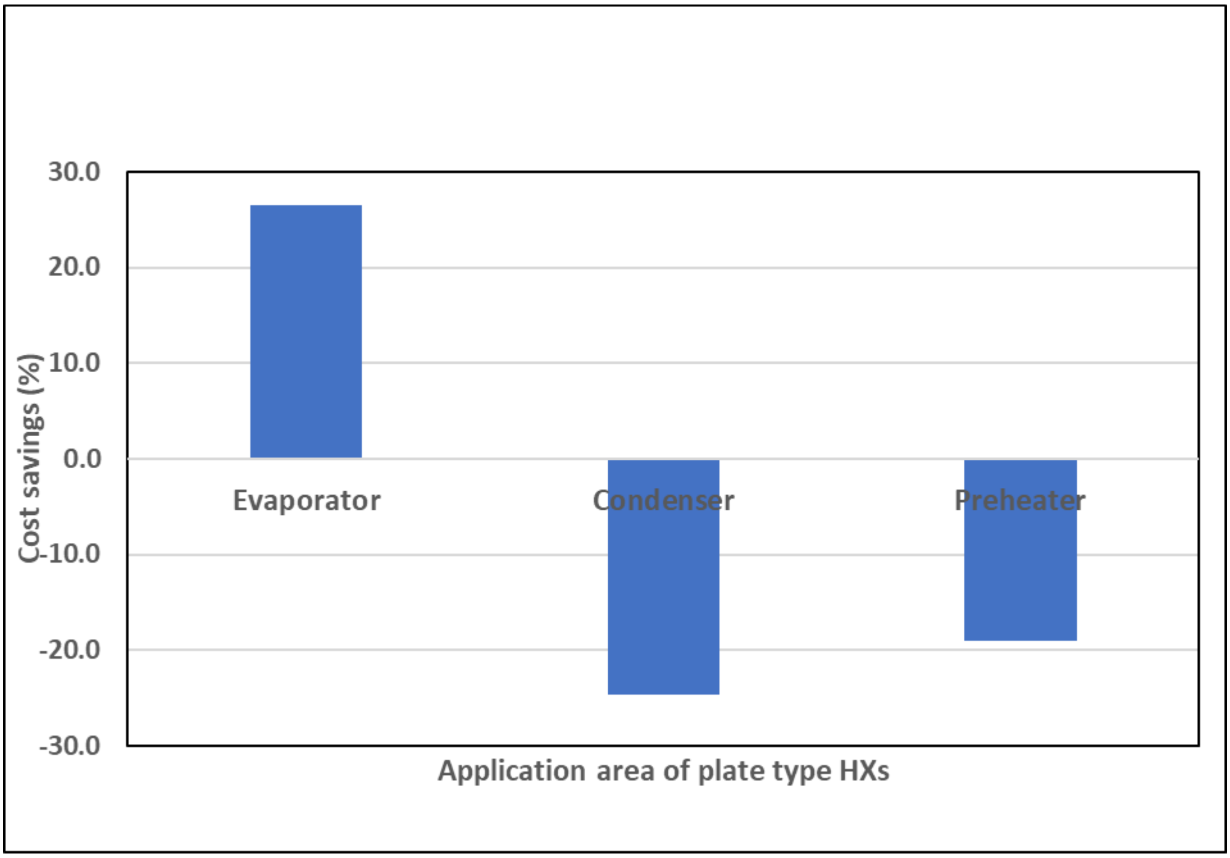

Figure 4.2 – Cost savings of GeoHex enabled plate type HXs instead of using standard HXs.

It is evident that GeoHex enabled plate type evaporator showed about 27% cost savings, whereas GeoHex enabled plate type condenser and preheater showed negative savings of about -25% and -19%, respectively.

4.2 Tubular type HXs

For cost analysis of three tubular type HXs with and without adoption of GeoHex materials, the estimated costs of these HXs have been considered. Manufacturers produced each HX twice for three application areas (preheater, evaporator, and condenser), ones for without adoption of GeoHex materials and considered as standard (STD) HXs and the other three ones are coated with the respective GeoHex materials and considered as GeoHex enabled (GeoHex) HXs, i.e., with the adoption of the respective GeoHex materials. To obtain the CAPEX of 3 GeoHex enabled tubular type HXs (preheater, condenser and evaporator), the respective coating deposition cost are added to the respective estimated CAPEX of 3 standard tubular type HXs. Table 4.3 lists the CAPEX of 3 standard and 3 GeoHex enabled tubular type HXs in units of €/m^2.

Table 4.3 – CAPEX of 3 standard and 3 GeoHex enabled tubular type HXs

Application area	Thermal capacity	Heat exchanged area	CAPEX of tubular type HXs (€/m^2)	
	(kW)	(m^2)	STD	GeoHex
Preheater	20	0.1	1064	1184
Condenser	9.5	0.63	844	1037
Evaporator	5	0.43	780	853

The heat transfer performance of these six tubular type HXs has been tested in mini ORC plant at CEA facilities and the overall HTC results have been obtained from CEA and given in Table 4.4.

Table 4.4 – Overall HTC results of tubular HXs and CAPEX of GeoHex enabled tubular HXs.

Application area	Overall HTC results ($W\ m^{-2}\ K^{-1}$)		Enhancement of HTC for adopting GeoHex materials	CAPEX of GeoHex enabled HXs considering the impacts of heat transfer performance results
	STD	GeoHex	(%)	(€/m²)
Preheater	3350	3908	16.7	1015
Condenser	1175	1198	2.0	1017
Evaporator	627	779	24.2	686

Based on the enhancement of HTC in GeoHex enabled tubular type HXs, the CAPEX of GeoHex enabled tubular type HXs per m^2 area have been calculated and obtained € 1015, €1017 and €686 per m^2 area for preheater, condenser and evaporator, respectively. The relative CAPEX costs of these three GeoHex enabled and the respective standard tubular type HXs are depicted in Figure 4.3. It is obtained that GeoHex enabled tubular type evaporator and preheater showed about 12% and 4.6% lower cost than those of the respective standard tubular type of evaporator and preheater, respectively. But GeoHex enabled tubular type condenser showed about 17% higher cost than that of standard tubular type condenser.

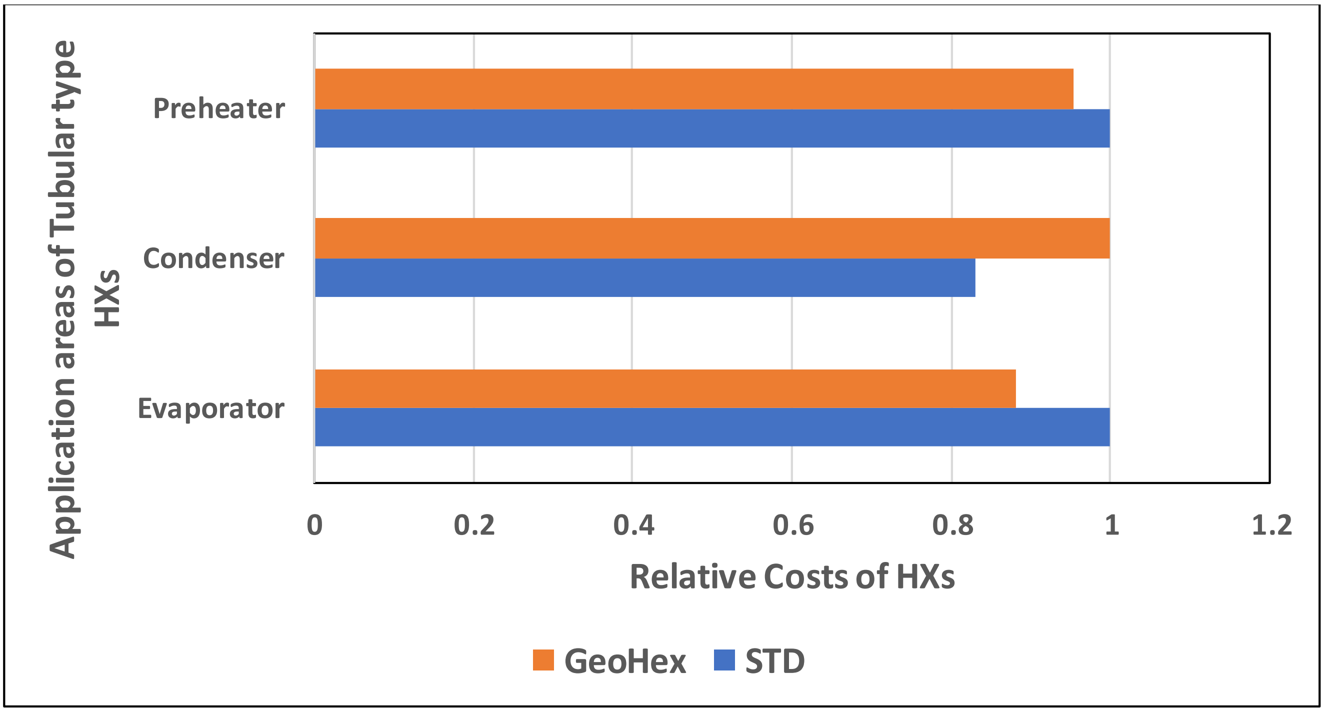

Figure 4.3 – Relative costs of three GeoHex enabled and respective standard tubular type HXs.

The cost savings per m^2 area of these three tubular type preheater, condenser and evaporator have also been calculated for adopting GeoHex enabled HXs instead of using the respective standard HXs. Figure 4.4 shows the cost savings in percentage of GeoHex enabled tubular type HXs instead of using the respective standard HXs.

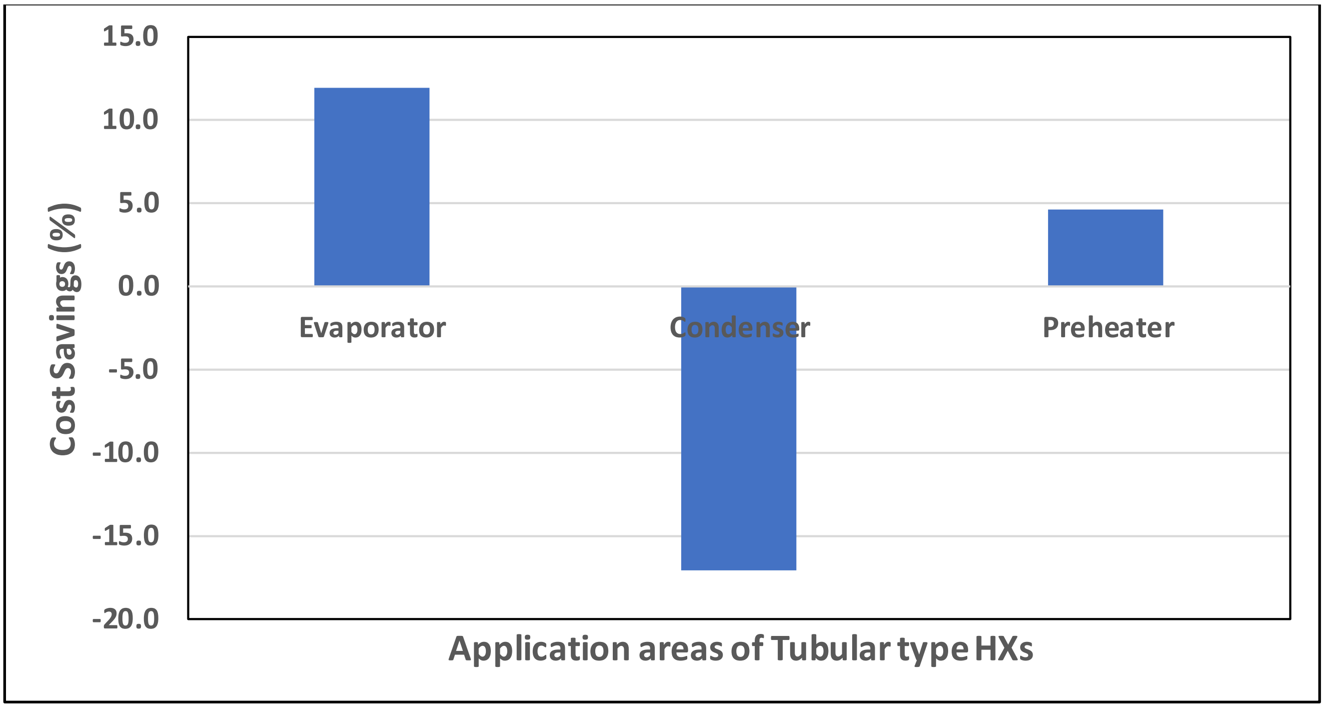

Figure 4.4 – Cost savings of GeoHex enabled tubular type HXs instead of using standard HXs.

It is evident that for adopting GeoHex enabled tubular type evaporator and preheater showed about 12% and 4.6% cost savings, respectively, instead of using the respective standard evaporator and preheater; whereas for adopting GeoHex enabled tubular type condenser instead of using the standard condenser showed negative savings of about -17%.

5. CONCLUSIONS

For the evaluation of cost performance, three plate andthree tubular type GeoHex enabled and standard HXs in three application areas (preheater, condenser & evaporator) have been considered and analysed. The manufacturing costs of all these twelve HXs have been estimated based on parametric cost modelling and justified those estimation with the purchasing costs of 'off-the-shelf' HXs and literature. With consideration of impacts of HTC enhancement or degradation in all GeoHex enabled HXs, the CAPEX of these HXs per m^2 have been evaluated. The main important findings are as follows:

- GeoHex enabled plate type evaporator showed about 27 % lower costs than that of the standard plate type evaporator.
- GeoHex enabled plate type condenser and preheater showed about 25 % and 19 % higher cost than those of standard plate type condenser and preheater, respectively.
- GeoHex enabled tubular type evaporator and preheater showed about 12% and 4.6% lower cost than those of the standard tubular type evaporator and preheater, respectively.
- GeoHex enabled tubular type condenser showed about 17% higher costs than those of standard tubular type condenser.

Finally, it is concluded that plate and tubular type GeoHex enabled evaporators showed a much better cost performance as compared to the respective standard HXs. Also, GeoHex enabled tubular type preheater showed a better cost performance as compared with the respective standard tubular preheater.