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Demonstrating a Refinery-adapted cluster-integrated strategy
to enable full-chain CCUS implementation - REALISE

D 3.3. Techno Economical Assessment (TEA) of CO_2 capture from Irving Oil Whitegate Refinery

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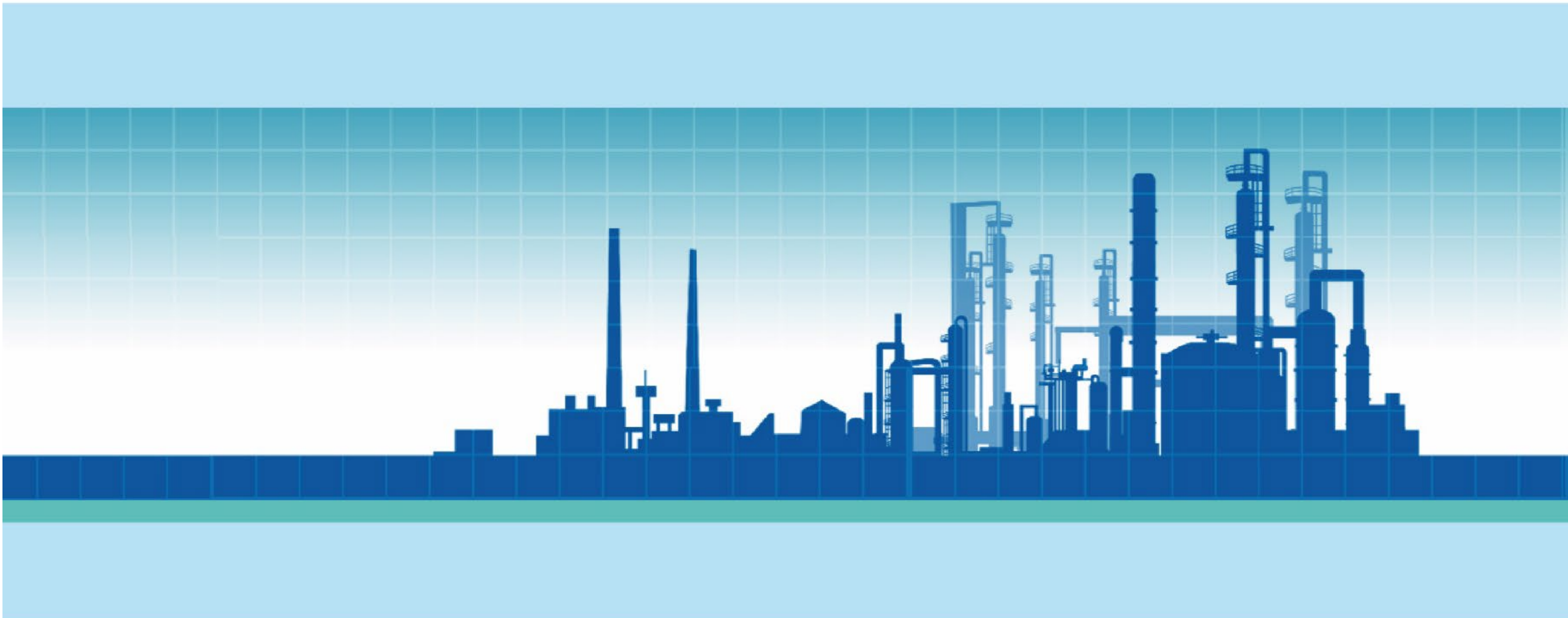

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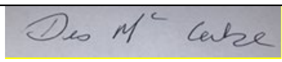
WP Leader or QA	Des McCabe		25/10/2023
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Disclaimer

1 Executive summary

A Techno-Economical Assessment (TEA) is performed based on the work done in Project REALISE Deliverable 3.2 (D 3.2) “Integration of CO_2 capture plant in refineries” where (4) scenarios for large-scale multi-stack CO_2 capture from the Irving Oil Whitegate refinery were defined.

A cluster of 8 different CO_2 sources (flue gas stacks) has been selected in the refinery to capture CO_2 from. The total yearly amount of CO_2 captured vary from 0.25 to 0.275 million metric ton per year.

Two (2) scenarios are based on the use of the benchmark solvent monoethanolamine (MEA), widely used in the CO_2 capture industry for capturing CO_2 from flue gasses. The other two scenarios are based on the new advanced amines based solvent HS3 Developed by NTNU and SINTEF in an earlier EU project HiPerCap.

For all the scenarios heat recovery is considered from the hot flue gasses to produce low pressure steam which is used as heat source for amine solvent regeneration.

Since the heat recovery from the hot flue gasses can only supply part of the required heat for solvent regeneration, two external heat sources are considered to supply the remaining heat i.e., 1. a natural gas fired boiler and 2. Import steam from a nearby power plant. Those two configuration scenarios are considered for both solvents.

In the work done in D 3.2, the selected process configuration has been optimized with respect to e.g., solvent flow rate to achieve low specific reboiler duty.

Based on the material balances for the four (4) cases as presented in D3.2 and the property data from the respective corresponding AspenPlus process simulations, process equipment summary sheets were prepared reflecting the key process parameters, material selection and dimensioning/sizing of the equipment.

The data from the equipment summary sheets formed the basis for the equipment costing and the costs for each piece of equipment are summarized in costing summary sheets per considered scenario. The pricing is done for the year 2023.

The Total Plant Costs for the four (4) cases is estimated by the so-called Enhanced Detailed Factor (EDF) method, developed by the University of South-Eastern Norway in cooperation with SINTEF Norway and updated in 2020 for use. The estimated TPC’s are for the year 2023.

For each individual piece of equipment, the total installed cost or TPC is estimated based on the price of the delivered equipment cost, whereby an expensive piece of equipment gets a lower installation factor than low priced equipment. Adjustments to this are based on certain plant specific construction factors.

The available plot space at Irving Oil Whitegate refinery has been evaluated to be adequate to locate the equipment associated with the design.

CO_2 capture fixed operational expenditures such as labour, maintenance, insurance, and variable operational costs such as for utilities like electricity and natural gas and consumables such as solvent make-up were identified.

Base prices for utilities and consumables were established for the economical assessments together. Also, the assumed plant life, yearly on-stream time and discount rate for the annualized capital expenditure calculations were defined.

Based on the resulting annualized CAPEX and OPEX costs and the yearly amount of CO_2 captured for each case, the specific CO_2 capture costs were determined for each scenario. The CO_2 capture costs of each scenario are compared and discussed.

The potential OPEX savings of nonlinear model-based predictive control (NMPC) has been evaluated with respect to optimized control against lowest possible steam use at any given time and against intensifying capture rates when energy prices are lower and vice versa. The calculated payback time of using NMPC in each individual scenario is evaluated to range from 4 to 25 weeks.

The use of plastics as material to metal for the columns and for the packings for the column was compared to the conventional use of metal. For the columns, metal is still the lowest cost material to use, whereas plastics has the lowest cost for the packing.

Finally, sensitivity analyses were performed on fixed capital, opex and carbon emission costs on the specific CO_2 capture costs. The main results can be seen in figure 1.1.1 The analysis showed higher sensitivity on the cost of energy compared to the CAPEX cost. Further the analysis showed that the cost ratio of MEA to HS3 is crucial for decision on which solvent system to employ, as even in high energy price scenario a HS3 solvent system is more costly to operate than a MEA system at base case solvent price ratios.

CO2 capture costs estimation sheet	Irving Oil Whitegate Refinery CO2 capture costs				
Capture scenario -->	MEA Case A	MEA Case B	HS3 Case A	HS3 Case B	
Annualized Capital Cost (AAC)	6.122.579,17	5.671.609,61	6.606.508,03	6.197.780,60	€
Total yearly variable OPEX	10.840.355,52	10.352.009,80	12.675.363,12	12.226.918,30	€
Total yearly fixed OPEX	3.733.014,12	3.493.048,56	3.805.104,73	3.607.820,24	€
CO2 capture cost (ex working capital)	78,22	82,39	92,97	92,85	€/MT

Figure 1.1.1 Cost of carbon capture for the four scenarios. For further details see Table 7.2.1.

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2 CO_2 capture from Irving Oil Whitegate refinery

2.1 Introduction

Carbon Capture Utilisation and Storage (CCUS) is crucial to the decarbonisation of energy-intensive industries with high levels of carbon dioxide (CO_2) emissions, such as oil refineries. The Irving Oil Whitegate refinery in Cork, Ireland, has been selected for this work package to investigate the feasibility of large-scale CO_2 capture from multiple refinery flue gas stacks.

In Project REALISE WP3 report D 3.2. "Integration of CO_2 capture plant in refineries", eight (8) different refinery CO_2 emitters (stacks) have been identified and selected for combined CO_2 capture at a total estimated rate of ca. 30 metric ton per hour (MT/h) based on their CO_2 content and based on the criteria as explained in D 3.2. It was concluded in the report that a combined single CO_2 Absorber column set-up will be the most efficient way to capture CO_2 from these multiple sources. The average CO_2 content of the combined flue gas is calculated at ca. 8 vol% on dry basis. Based on the measured impurities in the flue gasses, it was concluded that SO2 and NOx does not impose additional treating in the CO_2 capture process. The content of NOx could however impact the degradation rate of the used solvent.

Two amine solvents were considered in D 3.2 evaluations i.e. 30 wt% MEA as benchmark amine solvent, widely used in industrial CO_2 capture applications, and a 55 wt% newly developed amine solvent called HS3 consisting of a blend of 15 wt% 3-amino-1-propanol (AP) and 40 wt% 1-(2-hydroxyethyl) pyrrolidine (PRLD). This new solvent is mainly developed with the aim to decrease the cost of the CO_2 capture process, provide increased solvent stability and reduce the environmental impact compared to the benchmark solvent MEA.

2.2 CO_2 capture plant layout and selected CO_2 capture scenarios

As mentioned in the introduction, flue gasses from 8 (eight) stacks withing the Irving Oil Whitegate refinery are conveyed to the CO_2 capture plant with a total flow of ca. 225,210 Nm3/h. The flue gasses from the different stacks are available at high temperatures ranging from 250C to 600C.

The utility considered as the source of thermal duty for amine solvent regeneration is saturated LP steam at 130C. Minimizing the thermal duty for amine regeneration is important for the economic viability of large-scale CCUS.

Therefore, the hot flue gasses will be utilized to produce LP steam from the condensate returning from the amine solvent reboiler.

Close to each selected stack the respective flue gas will be cooled to 150C in a shell and tube heat exchanger to produce LP steam. The exchangers are sized for a maximum pressure drop of 20 mbar at the flue gas side.

Two additional stacks were selected from which to recover useful heat. They are however not considered for CO_2 capture due to too low CO_2 content.

The LP steam produced from the various refinery stacks is combined and routed to the CO_2 capture plant located within the refinery.

The LP steam produced from the flue gasses will not be sufficient to cover the total heat requirement for the CO_2 capture process. Therefore, 2 different scenarios are being considered to supplement the LP steam production from the flue gasses. The first scenario is by utilizing an auxiliary natural gas fired boiler. (Case A scenarios). The second scenario is the import of additional steam from an adjacent power plant (Case B scenarios).

For the Case A scenarios, the flue gas from the auxiliary boiler is combined with the flue gas from the different stacks and processed in the CO_2 capture plant.

The CO_2 capture process is described in detail in report D 3.2. The CO_2 capture process flow diagram is depicted in figure 2.2.1. It includes the equipment tag. no's, which are referred to in the next chapters. The stream numbers are taken from the D 3.2. report.

Cooling in the CO_2 capture plant is provided by circulating cooling water. The return cooling water is cooled by means of a dry-cooler as per common refinery practice.

An optimization study has been performed as part of D3.2. to find the optimum process conditions/parameters for the CO_2 capture process for operation with the MEA and HS3 solvent. The aim has been set at ca. 90% recovery of CO_2 at minimized heat consumption.

Table 2.2.1. provides a summary of the key results for the considered CO_2 capture scenarios.

	PFD	CO2 capture scenario			
Parameter	**Str. No.**	**MEA Case A**	**MEA Case B**	**HS3 Case A**	**HS3 Case B**
Flue gas flow to Absorber, Nm3/h	122	221,277	201,838	209,970	209,970
CO2 concentration, vol%	122	8.04	7.95	7.95	7.89
CO2 in flue gas to Absorber , T/h	122	34.92	31.50	32.77	32.52
Treated gas, Nm3/h	124	205,729	189,024	195,183	187,143
CO2 concentration treated gas, vol%	124	0.85	0.83	0.83	0.81
CO2 captured, T/h, calc	126	31.41	28.12	29.48	28.17
CO2 capture efficiency, %		89.9	89.3	90.0	86.6
Heat duty recovered from refinery flue gas, MW		18.17	18.17	18.17	18.17
Required reboiler duty, MW		33.05	29.61	24.45	23.31
Heat duty from auxiliary boiler, MW		14.88	N.A.	6.28	N.A.
Heat duty from steam import, MW		N.A.	11.44	N.A.	5.14
Specific Reboiler duty (SRD) , kWh/kg CO2		1.052	1.053	0.829	0.827

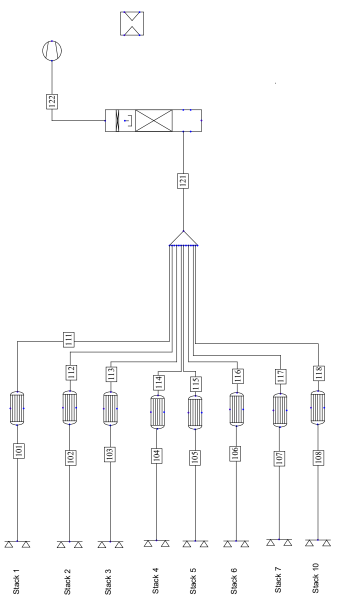
Table 2.2.1. Key CO_2 capture performance selected CO_2 capture scenarios

As can be seen from table 2.2.1. the HS3 solvent reduces the specific reboiler duty by ca. 21%. The HS3 solvent also lowers the amine circulation rate by ca. 24%, so reducing power consumption. Due to the slower kinetics and less favourable thermodynamics at low partial pressure of the HS3 solvent, a higher CO_2 absorption and desorption section is required. This will be further discussed in chapter 3.

From table 2.2.1. the CO_2 capture capacity for the Case B scenarios is reduced due to the fact that there will be no processing of flue gas from the natural gas fired boiler.

For MEA Case B, the CO_2 capture capacity will be ca. 90% of MEA Case A

For HS3 Case B, the CO_2 capture capacity will be ca. 95% of HS3 Case A.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Stack 3
Stack 4
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Stack 6
Stack 7
Stack 10

3 Equipment-type, material selection and sizing methodologies

3.1 Introduction

Equipment-type, material selection and dimensioning of the required CO_2 capture process equipment will provide the basis for the equipment costing, total plant cost estimation and the utility consumptions.

As mentioned in section 2.2, Case A scenarios for the MEA and HS3 solvent operation will be the design cases for the equipment because they represent the highest CO_2 capture rates due to co-processing of flue gas from the natural gas fired auxiliary boiler.

Only the flue gas boiler systems will be similar for the A & B cases.

In the following sections where the different types of equipment are discussed, reference is made to the PFD in figure 2.2.1.

3.2 Flue gas booster blower

For transporting the flue gasses from the stack all the way to the outlet of the Absorber column, flue gas pressure boosting will be required to overcome the pressure drop in the system.

Table 3.2.1. shows the pressure drops and pressure profile considered for the flue gas system.

Flue gas system Item / location	DP mbar	Pressure mbara
Flue gas stack outlet		1020
Ducting to boiler	10	
Flue gas boiler	20	
Flue gas boiler outlet ducting + combined ducting to DCC	20	
Inlet Direct Contact Cooler (DCC)		970
DCC column	10	
DCC outlet		960
Ducting from DCC to flue gas booster	5	
Booster inlet		955
Booster head	110	
Booster outlet		1065
Ducting between Booster outlet and Absorber	5	
Inlet Absorber		1060
Absorber	45	
Outlet Absorber		1015

Table 3.2.1. Pressure drop in flue gas system.

Both the Direct Contact Cooler (DCC) and Absorber column will be designed for very low pressure drop structured packing. The flue gas boosting system is designed for 3 fans in parallel operation to provide operational flexibility. Figure 3.2.1. depicts a flue gas centrifugal fan with associated in- and outlet piping.

The flue gas booster is designed for pressure head of 110 mbar and is located in between the DCC and Absorber column.

The material considered for the flue gas fans is stainless steel grade SS304L. The fan is of a centrifugal type providing compression in 1 stage.

Figure 3.2.1. Flue gas centrifugal fan

The flue gas fans /exhausters (C-101) are positioned downstream of the DCC (A-101) where the temperature is lowered to 25C.

The design and costing of the flue gas boosting system is determined by a selected European vendor. A summary of the flue gas booster can be found in section 3.10 and 3.11.

3.3 Columns

The following columns are present in the CO_2 capture process i.e., the DCC column A-101, the Absorber column (A-102) and the stripper column A-103.

For the DCC column a packing height of 3500 mm is considered based on actual experience. A low pressure drop type structured packing is selected which allows for a maximum pressure drop of 10 mbar. The diameters of the columns for MEA Case A and HS3 Case A are determined by use of packing vendor's column design software. Design % flood for sizing of the DCC column is taken as 85%. The loading data and fluid properties are taken from the D3.2 Aspen simulations.

The construction material considered for the DCC column is stainless steel grade SS304L.

The Absorber column (A-102) consists of an amine packing section for the absorption of CO_2 and a water wash packing section to control the amine circuit water balance by taking absorption heat from the circulating water and to minimize the solvent loss to atmosphere. Two packing sections of 7500 mm are considered for the MEA solvent and three packing sections of 7500 mm for the HS3 solvent due to the higher viscosity of this solvent resulting in slower kinetics.

A special low pressure structured packing type for amine CO_2 capture applications is selected for the amine sections for optimal gas liquid contact in amine applications.

A foaming factor of 0.85 and a flooding factor of 0.8 is considered for determining the diameter of the amine sections according to packing vendor recommendations. The required diameters of the absorbers for MEA and HS3 Case A are determined by use of packing vendor's column design software. The loading data and fluid properties are taken from the D 3.2 Aspen simulations.

For the water wash sections, a packing height of 3500 mm is considered. A low pressure drop structured packing is selected for this service. Design flooding factor is 0.85.

The Absorber column is designed for a total pressure drop of 45 mbar.

The diameters of these sections are the same as for their respective amine sections.

The stripper column (A-103) for the MEA solvent consists of two packing sections of 5000 mm each. For this service the 3rd generation random packing type is selected.

For the HS3 solvent an additional random packing section of 5000 mm is considered, so a total packing height of 15000 mm for the amine desorption section.

A 2500 mm water wash section in the top of the stripper is considered for both the MEA and HS3 solvent to minimize the solvent losses in the CO_2 product. For this section also a 3rd generation random packing is selected.

Further simulation work is needed to determine the needed packing height more accurately for the stripper column.

The type of packing chosen for the TEA is different from that used in the simulation work in D 3.2, this can influence the needed height of the individual packing section, this should be verified by further simulation work. The packing material chosen for the TEA is recommended to give lowest CAPEX. For the Absorber the structured packing selected has a high hydraulic capacity while maintaining efficient mass transfer resulting in lower diameter of the column and low flue gas pressure drop. For the stripper column the random packing is chosen due to the high liquid load in the tower and the lower final installed cost of this type of packing compared with structured packing.

For the hydraulic design of the amine desorption sections a foaming factor of 0.85 and a flooding factor of 0.85 is considered. The foaming factor is used rather than equivalent lower flooding factor in order to take into account correct pressure drop over the packing, i.e., maintaining an elevated pressure drop at larger tower diameter.

The wall thickness and estimated total weight calculations for the columns are determined by a Pentair approved pressure vessel vendor. The overall weight including the manholes and nozzles will be the basis for the cost estimation of the columns as discussed in chapter 4.

A summary of the column specifications can be found in sections 3.10 and 3.11.

3.4 Heat Exchangers

Shell and tube type heat exchangers are considered for the following services:

- Flue gas boilers (E-101, …., E-110)
- Stripper reboiler (E-116)

A BXM TEMA type heat exchanger as depicted in figure 3.4.1. can provide a low pressure drop design for the flue gas side of the flue gas boilers. Flue gas is flowing through the tube-side of the exchanger where it is cooled by evaporating steam condensate to produce steam at the shell side. Thermal designs for the flue gas boilers have been made for a 20 mbar max. pressure drop for the flue gas side. The boilers are assumed to be located as close as possible to their respective stack to minimize the heat losses.

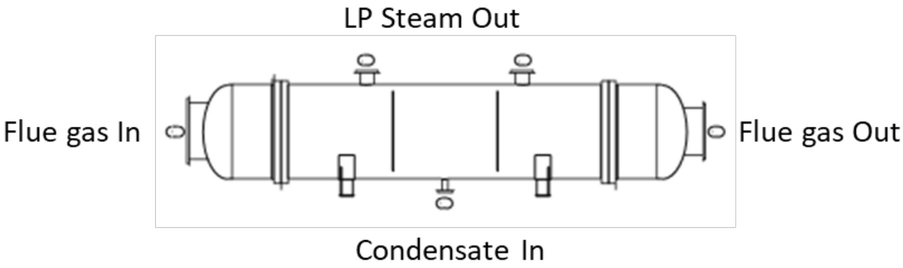


Figure 3.4.1. TEMA type BXM shell & tube exchanger

A kettle type (TEMA type BKU) shell & tube heat exchanger as depicted in figure 3.4.2. is selected for the amine stripper reboiler service. They are relatively insensitive to system hydraulics and provide a wide operating range between ca. 40-100% capacity.

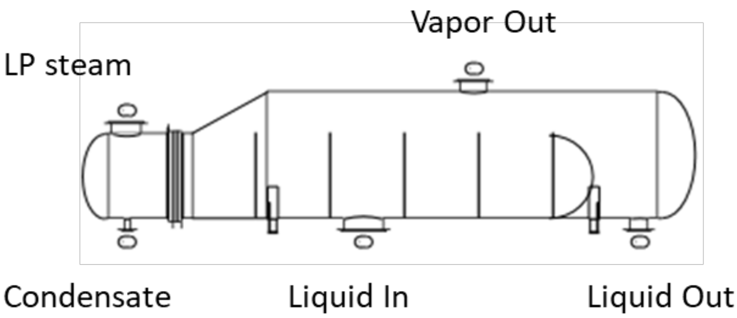


Figure 3.4.2. TEMA type BXM shell & tube exchanger

Two parallel reboilers have been considered in this service due to the large duty.

Aspen EDR is used for the thermal design of the shell & tube heat exchangers.

High temperature resistant P235 GH steel is selected for the flue gas boiler heat exchangers and SS316 for the stripper reboiler heat exchanger.

The estimated weight of the shell and tube heat exchanger will be the basis for the cost estimation as discussed in chapter 4.

Plate & frame heat exchangers are considered for the following services:

- Direct contact cooler column circulation cooler (E-111)
- Amine cooler (E-112)
- Combined amine cooler / heater (E-113)
- Stripper condenser / Gas cooler (E-115)

Plate & Frame heat exchangers are selected for these services for their compact design. Surface areas for these heat exchangers are estimated based on overall heat transfer coefficients from similar services used in actual CO_2 capture projects executed by Pentair. For the HS3 solvent the viscosity is significantly higher than for the MEA solvent, therefore resulting in lower overall heat transfer coefficients. This has been verified by Aspen EDR simulations.

The material for all the plate & frame heat exchangers is SS316.

The approach temperature to cooling water is 5C. For the combined amine cooler / heater a so-called Logarithmic Mean Temperature Difference (LMTD) of 10C is used.

A dry-cooler/air-cooler is selected for cooling of used cooling water as per refinery practise and preference. The design dry bulb temperature is 20C. This will set the design inlet cooling water temperature to 30C.

The yearly average cooling water (CW) inlet temperature will be ca. 20C. Both CW inlet temperatures are considered for determining the thermal design case for the cooling water exchangers. The cooling is considered to a 30wt% propylene glycol solution for freezing protection.

The material for dry-cooler tubes will be carbon steel (CS), the tube fins galvanized steel.

The sizing and costing of the air-cooler is done by selected European vendors.

A summary of the heat exchanger specifications can be found in sections 3.10 and 3.11.

3.5 Pumps

The following pump applications are present in the CO_2 capture plant:

- Flue gas scrubber (DCC) circulation pumps (P-101)
- Rich amine pumps (E-102)
- Lean amine pumps (E-103)
- Absorber wash water pumps (P-104)
- Stripper reflux pumps (P-105)
- Condensate feed pumps (P-120)
- Condensate return pumps (P-121)
- Cooling water circulation pumps (P-401)

The pumps are considered horizontal single stage, single suction centrifugal pumps.

The pumps are assumed to have an 80% hydraulic efficiency for estimating the power consumption.

Pump heads are estimated based on anticipated suction and discharge conditions in terms of elevations and pressure levels.

The following materials of construction are considered for the pump services:

P-101, P-104 & P-105: stainless steel grade SS316 due to potentially corrosive water

P-102 & P-103: stainless steel grade SS316 due to corrosive medium

P-120/121: Cast Iron due to non-corrosive environment.

P-401: Cast Iron due to non-corrosive environment.

The large capacity pumps are considered to have two (2) x 50% in operation with one (1) 50% pump as spare.

Cooling water pumps operate three (3) in parallel with 33.3% capacity each and one 33.3% capacity spare pump.

A summary of the pump specifications can be found in sections 3.10 and 3.11.

The capacity and the required pump head form the basis for the cost estimation.

3.6 Vessels / Process Drums

The following process vessels/drums are present in the CO_2 capture plant:

- Flue gas steam boilers condensate /steam separation drums (V-101., V-110)
- Amine activated carbon and particle filter (F-101)
- Stripper reflux drum (V-112)
- Steam condensate feed/flash tank (V-121)

The dimensions for these vessels are determined by use of in-house sizing tools for efficient vapor liquid separation and/or required liquid hold-up. The weight of the vessels is also estimated by use of an inhouse calculation tool. They form the basis for the costing for the vessels as discussed in chapter 4.

Carbon steel is selected as material for the flue gas steam boilers condensate / steam separation drums and condensate feed / flash tank, V-121 due to non-corrosive environment.

Amine filters and stripper reflux drum will be constructed in SS304 due to corrosive environment.

A summary of the process vessels specifications can be found in sections 3.10 and 3.11.

3.7 NG fired steam boilers (Package unit)

An auxiliary natural gas fired boiler X-101 as depicted in figure 3.7.1. is required for producing supplementary steam for the Stripper reboiler since the flue gas boilers alone cannot supply the required heat for the amine solvent regeneration. The required duties for the auxiliary boilers are specified for MEA and HS3 Case A in table 2.2.1.

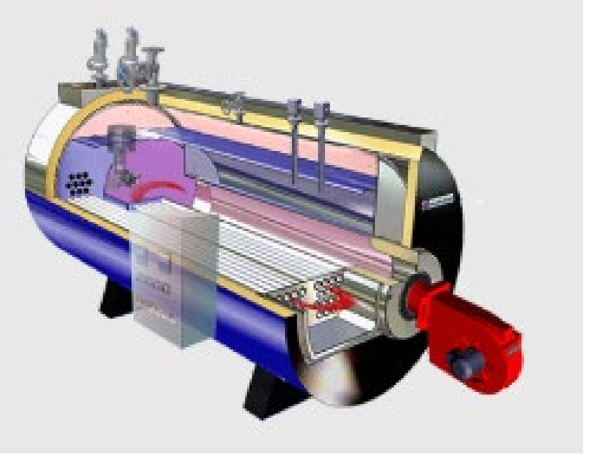


Figure 3.7.1. Natural gas fired steam boiler.

The auxiliary natural gas boiler specifications are summarized in section 3.10 & 3.11.

Vendor quotations has been received from European vendors for technical specifications of this burner / boiler package unit.

3.8 Amine Reclaimer system (Package unit)

The amine reclaiming system (X-102) is included to be able to remove degradation products of MEA and to recover valuable amine. The MEA in the loop is continuously degraded, especially by reaction with the oxygen containing compounds in the flue gas such as NO2 and SO2, but also by O2 and the temperature in the stripper.

A thermal reclaimer system has been considered for the MEA reclaiming process as depicted in figure 3.8.1.

Reclaiming is done by taking a side draw of the lean amine stream that leaves the stripper (and sending it to the reclaimer vessel).

It assumed that HS3 can be reclaimed in the same manner as MEA due to lack of data and experience on reclaiming HS3 solvent.

Here the heat stable salts could be broken back to MEA and acids by increasing the temperature, but this would cause the MEA to decompose and be lost.

Instead, the MEA solution is mixed with caustic soda (NaOH) which is a stronger base than MEA. As a result, the NaOH reacts with the acids that are bound in the heat stable salts and releases the MEA.

The MEA is afterwards evaporated and sent back to the absorber column. Approximately 90% of the MEA can be recovered by thermal reclaiming.

The estimated waste for the MEA solvent for the considered cases is approx. 70 kg/h. The type of waste handling is to be evaluated further it must be expected that the waste should be treated as hazardous chemical waste and must be incinerated by a waste handling facility. The nature of the waste especially for the HS3 solvent must be investigated further.

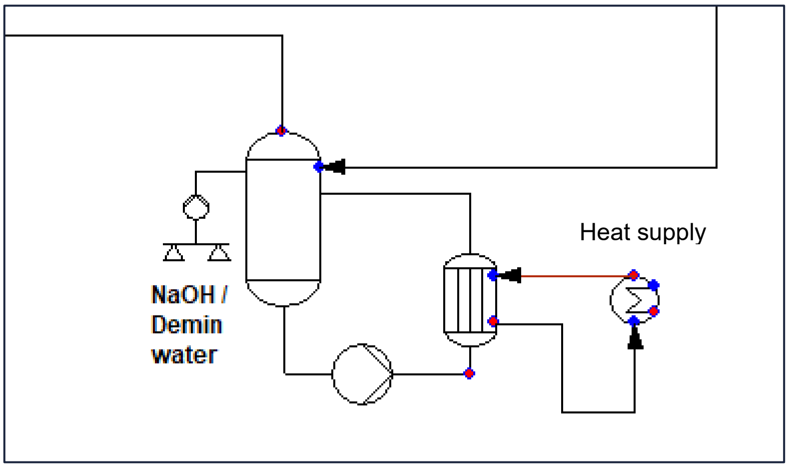


Figure 3.8.1. Thermal amine reclaiming system.

It is assumed that thermal reclaiming could also be used for cleaning and recovery of the HS3 solvent.

3.9 Amine supply system (Package unit)

An amine supply system has been considered to supply fresh solvent to the amine system to make-up for the losses due to degradation and evaporation losses. The supply system consists of an amine supply tank and an amine supply transfer pump.

3.10 Equipment summary sheets MEA Case A

Tables 3.10.1 – 3.10.8 summarizes the equipment specifications for scenario MEA Case A.

They form the basis for the equipment cost estimation for this case and is called the base case scenario for the MEA solvent.

For MEA Case B, the capacity is ca. 90% of Case A operation. This will be considered for estimating of the utility consumptions and the estimation of the equipment cost for this case. This will be further discussed in chapter 4 and 5.

Column summary	MEA Case A								
Tag. No.	**Item**	**Service**	**Type**	**Design code**	**Diameter, mm**	**Length / height, mm**	**Material of Construction**	**Estimated weight, kg**	**Remarks**
A-101	Column vessel	DCC / Flue gas scrubber		PED 2014/68/EU	5800	14.000	SS304	79.500	Including body flanges, nozzles, manholes and skirt
A-101	Demister		Mesh		5800		SS304		Pad thickness: 150 mm
A-101	Liquid distributor	Wash water			5800		SS304		1000 - 600 m3/h
A-101	Bed Limiter				5800		SS304		
A-101	Packing	Wash section	Structured packing		5800	3.500	SS304		
A-101	support plate				5800		SS304		
A-102	Column vessel	Absorber		PED 2014/68/EU	6050	38.500	SS304	120.000	Including body flanges, nozzles, manholes and skirt
A-102	Demister		Mesh		6050		SS304		Pad thickness: 150 mm
A-102	Liquid distributor	Wash water inlet			6050		SS304		655-400 m3/h
A-102	Packing	Wash section	Structured packing		6050	3.500	SS304		
A-102	Liquid collector	Wash water			6050		SS304		655-400 m3/h
A-102	Liquid distributor	Lean amine solvent inlet			6050		SS304		560-335 m3/h, density = 1054 kg/m3, visc. = 3.3 cP
A-102	Packing	Amine section	Structured packing		6050	7.500	SS304		
A-102	support plate				6050		SS304		
A-102	Liquid collector	Amine solvent			6050		SS304		545 -330 m3/h, density = 1100 kg/m3, viscosity = 1,7 cP
A-102	Liquid distributor	Amine solvent			6050		SS304		545 -330 m3/h, density = 1100 kg/m3, viscosity = 1,7 cP
A-102	Packing	Amine section	Structured packing		6050	7.500	SS304		
A-102	gas inlet distributor	Gas inlet			6050		SS304		Gas flow = 241000 act. m3/h
A-103	Column vessel	Stripper		PED 2014/68/EU	3150	27.300	SS304	60.500	
A-103	Demister		Mesh		3150		SS304		
A-103	Liquid distributor	Inlet reflux water					SS304		14 - 8.5 m3/h
A-103	Bed Limiter				3150		SS304		
A-103	Packing	Wash section	Random packing		3150	2.500	SS304		
A-103	Flashing feed gallery	Wash section			3150		SS304		830 - 500 m3/h, Frac V =0.2
A-103	Liquid distributor	Amine solvent			3150		SS304		830 - 500 m3/h, density = 1059 kg/m3, visc. = 0.57 cP
A-103	Bed Limiter				3150		SS304		
A-103	Packing	Amine section	Random packing		3150	5.000	SS304		
A-103	support plate				3150		SS304		
A-103	Liquid collector	Amine solvent			3150		SS304		580 - 350 m3/h, density = 1045 kg/m3, visc. = 0.58 cP
A-103	Liquid distributor	Amine solvent			3150		SS304		580 - 350 m3/h, density = 1045 kg/m3, visc. = 0.58 cP
A-103	Bed Limiter				3150		SS304		
A-103	Packing	Amine section	Random packing		3150	5.000	SS304		
A-103	support plate				3150		SS304		
A-103	Liquid collector	Amine solvent			3150		SS304		620 - 370 m3/h, density = 998 kg/m3, visc. = 0.48 cP

Table 3.10.1. Column summary sheet MEA Case A

Vessel Summary	MEA Case A												
											Material of Construction		
Tag. No.	Item	Service	Type	Design code	Diameter, mm	Length, mm	Volume, m3	Internal	Filter Adsorbent	Adsorbent weight, kg	Shell	Internals	Estimated total weight, kg
V-101	Vessel	LP steam / condensate	Hor.	PED 2014/68/EU	900	3000	2.1	Separators	N.A.	N.A.	CS	CS	1,460
V-101	Internals	Separators, flow distributors											
V-102	Vessel	LP steam / condensate	Hor.	PED 2014/68/EU	1250	2750	3.9	Separators	N.A.	N.A.	CS	CS	1,640
V-102	Internals	Separators, flow distributors											
V-103	Drum	LP steam / condensate	Hor.	PED 2014/68/EU	1600	3200	7.5	Separators	N.A.	N.A.	CS	CS	2,150
V-103	Internals	Separators, flow distributors											
V-104	Drum	LP steam / condensate	Hor.	PED 2014/68/EU	1000	3350	2.9	Separators	N.A.	N.A.	CS	CS	1,520
V-104	Internals	Separators, flow distributors											
V-105	Drum	LP steam / condensate	Hor.	PED 2014/68/EU	1400	3200	5.6	Separators	N.A.	N.A.	CS	CS	1,880
V-105	Internals	Separators, flow distributors											
V-106A	Drum	LP steam / condensate	Hor.	PED 2014/68/EU	1700	2700	7.4	Separators	N.A.	N.A.	CS	CS	2,140
V-106A	Internals	Separators, flow distributors											
V-106B	Drum	LP steam / condensate	Hor.	PED 2014/68/EU	1700	2700	7.4	Separators	N.A.	N.A.	CS	CS	2,140
V-106B	Internals	Separators, flow distributors											
V-107	Drum	LP steam / condensate	Hor.	PED 2014/68/EU	1800	3150	9.5	Separators	N.A.	N.A.	CS	CS	2,440
V-107	Internals	Separators, flow distributors											
V-108	Drum	LP steam / condensate	Hor.	PED 2014/68/EU	850	3600	9.5	Separators	N.A.	N.A.	CS	CS	1,410
V-108	Internals	Separators, flow distributors											
V-109	Drum	LP steam / condensate	Hor.	PED 2014/68/EU	600	2500	0.8	Separators	N.A.	N.A.	CS	CS	1,020
V-109	Internals	Separators, flow distributors											
V-110A	Drum	LP steam / condensate	Hor.	PED 2014/68/EU	700	1300	0.6	Separators	N.A.	N.A.	CS	CS	980
V-110A	Internals	Separators, flow distributors											
V-110B	Drum	LP steam / condensate	Hor.	PED 2014/68/EU	700	1300	0.6	Separators	N.A.	N.A.	CS	CS	980
V-110B	Internals	Separators, flow distributors											
F-101A	Vessel	Amine activated Carbon /particle filter	Vert.	PED 2014/68/EU	2000	3500	13.1				SS304		3,700
F-101A	Adsorbent	Activated Carbon		PED 2014/68/EU	2000	3500	11		Activated Carbon	6050 (per vessel)	SS304		
F-101B	Vessel	Amine activated Carbon /particle filter	Vert.	PED 2014/68/EU	2000	3500	13.1				SS304		3,700
F-101B	Adsorbent	Activated Carbon		PED 2014/68/EU	2000	3500	11		Activated Carbon	6050 (per vessel)	SS304		
V-112	Drum	Stripper reflux drum	Vert.	PED 2014/68/EU	2000	3000	11.5		N.A.	N.A.	SS304		2,400
V-121	Drum	Condensate feed / flash tank	Hor.	PED 2014/68/EU	1700	4250	10.9		N.A.	N.A.	CS		2,400

Table 3.10.2. Vessel summary sheet MEA Case A

Blower summary MEA Case A

Tag. No.	Service	Type	Quantity	Design inlet flow, kg/hr	MW, kg/kmol	Suction pressure, bara	Discharge pressure, bara	Inlet temperature, °C	Estimated absorbed power, kW	Installed power, kW	Material of Construction Casing	Material of Construction Impeller	Estimated total weight, kg
C-101A	Exhauster	Centrifugal	1	95500	28.84	0.95	1.055	35	300	355	SS304	SS304	5140
C-101B	Exhauster	Centrifugal	1	95500	28.84	0.95	1.055	35	300	355	SS304	SS304	5140
C-101C	Exhauster	Centrifugal	1	95500	28.84	0.95	1.055	35	300	355	SS304	SS304	5140

Table 3.10.3. Blower summary MEA Case A

Heat exchanger Summary Shell and Tube	MEA Case A																	
										Tubes		Shell		Material of Construction				
Tag. No.	Service	Medium hot side	Medium cold side	TEMA Type	Quantity	Parallel	In series	Duty, kW	Effective surface area , m2	OD, mm	Length, m	OD, mm	Length, m	Shell side	Tube side	Estimated total weight, kg	Remark 1	Remark 2
E-101	Flue gas boiler	Flue gas (TS)	Water / Steam (SS)	BXM	1	1	1	1040	175	19.05	3050	930	3050	P235 GH	P235 GH	7,145	In combination with drum V-101	Designed for DP=20mbar
E-102	Flue gas boiler	Flue gas (TS)	Water / Steam (SS)	BXM	1	1	1	1230	320	19.05	2750	1330	2750	P235 GH	P235 GH	14,060	In combination with drum V-102	Designed for DP=20mbar
E-103	Flue gas boiler	Flue gas (TS)	Water / Steam (SS)	BXM	1	1	1	2565	530	19.05	3200	1580	3200	P235 GH	P235 GH	22,740	In combination with drum V-103	Designed for DP=20mbar
E-104	Flue gas boiler	Flue gas (TS)	Water / Steam (SS)	BXM	1	1	1	1630	228	19.05	3350	1000	3350	P235 GH	P235 GH	9,970	In combination with drum V-104	Designed for DP=20mbar
E-105	Flue gas boiler	Flue gas (TS)	Water / Steam (SS)	BXM	1	1	1	2230	412	19.05	3200	1380	3200	P235 GH	P235 GH	16,361	In combination with drum V-105	Designed for DP=20mbar
E-106A	Flue gas boiler A	Flue gas (TS)	Water / Steam (SS)	BXM	1	1	1	2131	537	19.05	2700	1730	2700	P235 GH	P235 GH	23,850	In combination with drum V-106A	Designed for DP=20mbar
E-106B	Flue gas boiler B	Flue gas (TS)	Water / Steam (SS)	BXM	1	1	1	2131	537	19.05	2700	1730	2700	P235 GH	P235 GH	23,850	In combination with drum V-106B	Designed for DP=20mbar
E-107	Flue gas boiler	Flue gas (TS)	Water / Steam (SS)	BXM	1	1	1	3443	706	19.05	3150	1830	3150	P235 GH	P235 GH	29,412	In combination with drum V-107	Designed for DP=20mbar
E-108	Flue gas boiler	Flue gas (TS)	Water / Steam (SS)	BXM	1	1	1	1516	178	19.05	3600	850	3600	P235 GH	P235 GH	6,800	In combination with drum V-108	Designed for DP=20mbar
E-109	Flue gas boiler	Flue gas (TS)	Water / Steam (SS)	BXM	1	1	1	248	62	19.05	2550	600	2550	P235 GH	P235 GH	2,600	In combination with drum V-109	Designed for DP=20mbar
E-110A	Flue gas boiler A	Flue gas (TS)	Water / Steam (SS)	BXM	1	1	1	104	42	19.05	1350	700	1350	P235 GH	P235 GH	2,500	In combination with drum V-110	Designed for DP=20mbar
E-110B	Flue gas boiler B	Flue gas (TS)	Water / Steam (SS)	BXM	1	1	1	104	42	19.05	1350	700	1350	P235 GH	P235 GH	2,500	In combination with drum V-110	Designed for DP=20mbar
E-116A	Stripper reboiler	LP steam	Amine	BKU	1	1	1	16570	1052	19.05	5850	1380 / 2060	5850	SS304	SS304	33,383		
E-116B	Stripper reboiler	LP steam	Amine	BKU	1	1	1	16570	1052	19.05	5850	1380 / 2060	5850	SS304	SS304	33,383		

Table 3.10.4. Heat Exchanger summary (S&T) MEA Case A

Heat exchanger summary	MEA Case A										
Plate and Frame											
										Material of Construction	
Tag. No.	**Service**	**Medium hot side**	**Medium cold side**	**Type**	**Quantity**	**Parallel**	**In series**	**Duty, kW**	**Heat transfer area , m2**	**Shell or Headers**	**Tubes or Plates**
E-111	DCC / FGS water cooler	Process water	Cooling water	Plate & Frame	1	1	1	25400	900	SS316	SS316
E-112	Amine cooler	Lean Amine	Cooling water	Plate & Frame	1	1	1	5990	137	SS316	SS316
E-113	Combined amine cooler / heater	Lean amine	Rich amine	Plate & Frame	1	1	1	38190	1466	SS316	SS316
E-114	Absorber top cooler	Process water	Cooling water	Plate & Frame	1	1	1	16100	415	SS316	SS316
E-115	Stripper condenser / Gas cooler	CO2 gas / water	Cooling water	Plate & Frame	1	1	1	10512	223	SS316	SS316

Table 3.10.5. Heat Exchanger summary (PFHE) MEA Case A

Heat exchanger Summary Dry-cooler	MEA Case A											
											Material of Construction	
Tag. No.	Service	Medium hot side	Medium cold side	Type	Quantity	Parallel	In series	Duty, kW	Estimated plot area, m2	Power consumption fans, kW	Tubes	Fins
E-401	Cooling water circulation cooler	Cooling water (20 wt% glycol)	Air	Aircooler	1	1	1	52,000	1090	2070	CS	Galvanized steel

Table 3.10.6. Heat Exchanger summary sheet (Dry-cooler) MEA Case A

Pump Summary	MEA Case A									
									Material of Construction	
Tag. No.	Service	Type	Quantity	Design flowrate, m3/hr	Fluid density, kg/m3	Diff. head @ design flowrate, bar	Estimated absorbed power, kW	Installed power, kW	Casing	Impeller
P-101A	Flue gas scrubber circ. pump	Centrifugal	1	500	1000	2	35	45	SS316	SS316
P-101B	Flue gas scrubber circ. pump	Centrifugal	1	500	1000	2	35	45	SS316	SS316
P-101S	Flue gas scrubber circ. pump	Centrifugal	1	500	1000	2	35	45	SS316	SS316
P-102A	Rich amine pump	Centrifugal	1	300	1100	2.5	25	30	SS316	SS316
P-102B	Rich amine pump	Centrifugal	1	300	1100	2.5	25	30	SS316	SS316
P-102S	Rich amine pump	Centrifugal	1	300	1100	2.5	25	30	SS316	SS316
P-103A	Lean amine pump	Centrifugal	1	275	1000	3.2	30	40	SS316	SS316
P-103B	Lean amine pump	Centrifugal	1	275	1000	3.2	30	40	SS316	SS316
P-103S	Lean amine pump	Centrifugal	1	275	1000	3.2	30	40	SS316	SS316
P-104A	Wash water circ. Pump	Centrifugal	1	350	1000	2.5	35	45	SS316	SS316
P-104B	Wash water circ. Pump	Centrifugal	1	350	1000	2.5	35	45	SS316	SS316
P-104S	Wash water circ. Pump	Centrifugal	1	350	1000	2.5	35	45	SS316	SS316
P-105A	Stripper reflux pump	Centrifugal	1	15	1000	1.7	0.8	1	SS316	SS316
P-105S	Stripper reflux pump	Centrifugal	1	15	1000	1.7	0.8	1	SS316	SS316
P-120A	Condensate feed pump	Centrifugal	1	55	1000	2.5	4.8	6	Cast Iron	Cast Iron
P-120S	Condensate feed pump	Centrifugal	1	55	1000	2.5	4.8	6	Cast Iron	Cast Iron
P-121A	Condensate return pump	Centrifugal	1	N.A.	N.A.	N.A.	N.A.		Cast Iron	Cast Iron
P-121S	Condensate return pump	Centrifugal	1	N.A.	N.A.	N.A.	N.A.		Cast Iron	Cast Iron
P-401A	cooling water pump	Centrifugal	1	1,200	1000	2.5	105	130	Cast Iron	Cast Iron
P-401B	cooling water pump	Centrifugal	1	1,200	1000	2.5	105	130	Cast Iron	Cast Iron
P-401C	cooling water pump	Centrifugal	1	1,200	1000	2.5	105	130	Cast Iron	Cast Iron
P-401S	cooling water pump (spare)	Centrifugal	1	1,200	1000	2.5	105	130	Cast Iron	Cast Iron

Table 3.10.7. Pump summary sheet MEA Case A

Package Unit Summary	MEA Case A		
Tag. No.	**Service**	**Capacity / Duty**	**Estimated plot (LxWxH), m**
X-101	Natural gas fired boiler unit	23500 kg/h LP steam production	9000 x 4110 x 4610
X-102	Amine reclaimer unit	450 kg/h	
X-103	Amine solvent supply system	45 kg/h average	
X-103	Initial MEA solvent filling (45 wt%)	150 m3	

Table 3.10.8. Package unit summary sheet MEA Case A

3.11 Equipment summary sheet HS3 Case A

Tables 3.11.1 – 3.11.6 summarizes the equipment specifications for scenario HS3 Case A.

They form the basis for the equipment cost estimation for this case and is called the base case scenario for the HS3 solvent.

For HS3 Case B, the capacity is ca. 95% of Case B operation. This will be taken into account for estimating of the utility consumptions and the equipment cost for this case. This will be further discussed in chapter 4 and 5.

Column Summary	HS3 Case A								
Tag. No.	Item	Service	Type	Design code	Diameter, mm	Length / height, mm	Material of Construction	Estimated weight, kg	Remarks
A-101	Column vessel	DCC / Flue gas scrubber		PED 2014/68/EU	5800	14.000	SS304	79.500	Including body flanges, nozzles, manholes and skirt
A-101	Demister		Mesh		5800		SS304		Pad thickness: 150 mm
A-101	Liquid distributor	Wash water			5800		SS304		1000 - 600 m3/h
A-101	Bed Limiter				5800		SS304		
A-101	Packing	Wash section	Structured packing		5800	3.500	SS304		
A-101	support plate				5800		SS304		
A-102	Column vessel	Absorber		PED 2014/68/EU	5800		SS304	149.000	Including body flanges, nozzles, manholes and skirt
A-102	Demister		Mesh		5800		SS304		Pad thickness: 150 mm
A-102	Liquid distributor	Wash water inlet			5800		SS304		450-270 m3/h
A-102	Packing	Wash section	Structured packing		5800	3.500	SS304		
A-102	Liquid collector	Wash water			5800		SS304		480-290 m3/h
A-102	Liquid distributor	Lean amine solvent inlet			5800		SS304		415-250 m3/h, density = 1056 kg/m3, visc. = 4.8 cP
A-102	Packing	Amine section #1	Structured packing		5800	7.500	SS304		
A-102	support plate				5800		SS304		
A-102	Liquid collector	Amine solvent			5800		SS304		350 -210 m3/h, density = 1096 kg/m3, visc. = 2.53 cP
A-102	Liquid distributor	Amine solvent			5800		SS304		350 -210 m3/h, density = 1096 kg/m3, visc. = 2.53 cP
A-102	Packing	Amine section #2	Structured packing		5800	7.500	SS304		
A-102	support plate				5800		SS304		
A-102	Liquid collector	Amine solvent			5800		SS304		220 -134 m3/h, density = 1112 kg/m3, visc. = 3.24 cP
A-102	Liquid distributor	Amine solvent			5800		SS304		220 -134 m3/h, density = 1112 kg/m3, visc. = 3.24 cP
A-102	Packing	Amine section	Structured packing		5800	7.500	SS304		
A-102	support plate				5800		SS304		
A-102	gas inlet distributor	Gas inlet			5800		SS304		actual 230 m3/h
A-103	Column vessel	Stripper		PED 2014/68/EU	2750	34.360	SS304	42.000	Including body flanges, nozzles, manholes and skirt
A-103	Demister		Mesh		2750		SS304		
A-103	Liquid distributor	Inlet reflux water			2750		SS304		7 - 4.5 m3/h
A-103	Bed Limiter				2750		SS304		
A-103	Packing	Wash section	Random packing		2750	2.500	SS304		
A-103	Flashing feed gallery	Amine 2-phase feed inlet			2750		SS304		330 - 130 m/h, Frac V = 0.03
A-103	Liquid distributor	Amine solvent			2750		SS304		330 - 200 m3/h, density = 1066 kg/m3, visc. = 1.31 cP
A-103	Bed Limiter				2750		SS304		
A-103	Packing	Amine section #1	Random packing		2750	5.000	SS304		
A-103	support plate				2750		SS304		
A-103	Liquid collector	Amine solvent			2750		SS304		390 - 115 m3/h, density = 1065 kg/m3, visc. = 1.19 cP
A-103	Liquid distributor	Amine solvent			2750		SS304		390 - 115 m3/h, density = 1065 kg/m3, visc. = 1.19 cP
A-103	Bed Limiter				2750		SS304		
A-103	Packing	Amine section #2	Random packing		2750	5.000	SS304		
A-103	Liquid collector	Amine solvent			2750		SS304		440 - 260 m3/h, density = 1026 kg/m3, visc. = 0.85 cP
A-103	Liquid distributor	Amine solvent			2750		SS304		440 - 260 m3/h, density = 1026 kg/m3, visc. = 0.85 cP
A-103	Bed Limiter				2750		SS304		
A-103	Packing	Amine section #3	Random packing		2750	5.000	SS304		
A-103	support plate				2750		SS304		
A-103	Liquid collector	Amine solvent			2750		SS304		430 - 250 m3/h, density = 999 kg/m3, visc. = 0.80 cP

Table 3.11.1. Column summary sheet HS3 Case A

Vessel Summary	HS3 Case A													
											Material of Construction			
Tag. No.	Item	Service	Type	Design code	Diameter, mm	Length, mm	Volume, m3	Internal	Filter Adsorbent	Adsorbent weight, kg	Shell	Internals	Estimated total weight, kg	Remarks
V-101	Vessel	LP steam / condensate	Hor.	PED 2014/68/EU	900	3000	2.1	Separators	N.A.	N.A.	CS	CS	1,460	Connected to E-101
V-101	Internals	Separators, flow distributors												Demister, flow distributors
V-102	Vessel	LP steam / condensate	Hor.	PED 2014/68/EU	1250	2750	3.9	Separators	N.A.	N.A.	CS	CS	1,640	Connected to E-102
V-102	Internals	Separators, flow distributors												Demister, flow distributors
V-103	Drum	LP steam / condensate	Hor.	PED 2014/68/EU	1600	3200	7.5	Separators	N.A.	N.A.	CS	CS	2,150	Connected to E-103
V-103	Internals	Separators, flow distributors												Demister, flow distributors
V-104	Drum	LP steam / condensate	Hor.	PED 2014/68/EU	1000	3350	2.9	Separators	N.A.	N.A.	CS	CS	1,520	Connected to E-104
V-104	Internals	Separators, flow distributors												Demister, flow distributors
V-105	Drum	LP steam / condensate	Hor.	PED 2014/68/EU	1400	3200	5.6	Separators	N.A.	N.A.	CS	CS	1,880	Connected to E-105
V-105	Internals	Separators, flow distributors												Demister, flow distributors
V-106A	Drum	LP steam / condensate	Hor.	PED 2014/68/EU	1700	2700	7.4	Separators	N.A.	N.A.	CS	CS	2,140	Connected to E-106A
V-106A	Internals	Separators, flow distributors												Demister, flow distributors
V-106B	Drum	LP steam / condensate	Hor.	PED 2014/68/EU	1700	2700	7.4	Separators	N.A.	N.A.	CS	CS	2,140	Connected to E-106B
V-106B	Internals	Separators, flow distributors												Demister, flow distributors
V-107	Drum	LP steam / condensate	Hor.	PED 2014/68/EU	1800	3150	9.5	Separators	N.A.	N.A.	CS	CS	2,440	Connected to E-107
V-107	Internals	Separators, flow distributors												Demister, flow distributors
V-108	Drum	LP steam / condensate	Hor.	PED 2014/68/EU	850	3600	9.5	Separators	N.A.	N.A.	CS	CS	1,410	Connected to E-108
V-108	Internals	Separators, flow distributors												Demister, flow distributors
V-109	Drum	LP steam / condensate	Hor.	PED 2014/68/EU	600	2500	0.8	Separators	N.A.	N.A.	CS	CS	1,020	Connected to E-109
V-109	Internals	Separators, flow distributors												Demister, flow distributors
V-110A	Drum	LP steam / condensate	Hor.	PED 2014/68/EU	700	1300	0.6	Separators	N.A.	N.A.	CS	CS	980	Connected to E-110A
V-110A	Internals	Separators, flow distributors												Demister, flow distributors
V-110B	Drum	LP steam / condensate	Hor.	PED 2014/68/EU	700	1300	0.6	Separators	N.A.	N.A.	CS	CS	980	Connected to E-110B
V-110B	Internals	Separators, flow distributors												Demister, flow distributors
F-101A	Vessel	Amine activated Carbon /particle filter	Vert.	PED 2014/68/EU	1750	3500	9.8				SS304		3,060	Adjusted for flowrate between MEA and HS3 case
F-101A	Adsorbent	Activated Carbon		PED 2014/68/EU	1750	3500	8.4		Activated Carbon	4620 (per vessel)	SS304			Size adjusted for flowrate between MEA and HS3 case
F-101B	Vessel	Amine activated Carbon /particle filter	Vert.	PED 2014/68/EU	1750	3500	9.8				SS304		3,060	Size adjusted for flowrate between MEA and HS3 case
F-101B	Adsorbent	Activated Carbon		PED 2014/68/EU	1750	3500	8.4		Activated Carbon	4620 (per vessel)	SS304			Size adjusted for flowrate between MEA and HS3 case
V-112	Drum	Stripper reflux drum	Vert.	PED 2014/68/EU	2000	3000	11.5		N.A.	N.A.	SS304		2,400	Size adjusted for flowrate between MEA and HS3 case
V-121	Drum	Condensate feed / flash tank	Hor.	PED 2014/68/EU	1450	3650	6.8		N.A.	N.A.	CS		1,990	Size adjusted for flowrate between MEA and HS3 case

Table 3.11.2. Vessel summary sheet HS3 Case A

Blower Summary	HS3 Case A													
											Material of Construction			
Tag. No.	Service	Type	Quantity	Design inlet flow, kg/hr	MW, kg/kmol	Suction pressure, bara	Discharge pressure, bara	Inlet temperature, °C	Estimated absorbed power, kW	Installed power, kW	Casing	Impeller	Estimated total weight, kg	Remarks
C-101A	Exhauster	Centrifugal	1	95500	28.84	0.95	1.055	35	300	355	SS304	SS304	5140	Including motor
C-101B	Exhauster	Centrifugal	1	95500	28.84	0.95	1.055	35	300	355	SS304	SS304	5140	Including motor
C-101C	Exhauster	Centrifugal	1	95500	28.84	0.95	1.055	35	300	355	SS304	SS304	5140	Including motor

Table 3.11.3. Blower summary HS3 Case A

Heat exchanger Summary Shell and Tube	MEA Case A									Tubes		Shell		Material of Construction				
Tag. No.	Service	Medium hot side	Medium cold side	TEMA Type	Quantity	Parallel	In series	Duty, kW	Effective surface area , m2	OD, mm	Length, m	OD, mm	Length, m	Shell side	Tube side	Estimated total weight, kg	Remark 1	Remark 2
E-101	Flue gas boiler	Flue gas (TS)	Water / Steam (SS)	BXM	1	1	1	1040	175	19.05	3050	930	3050	P235 GH	P235 GH	7,145	In combination with drum V-101	Designed for DP=20mbar
E-102	Flue gas boiler	Flue gas (TS)	Water / Steam (SS)	BXM	1	1	1	1230	320	19.05	2750	1330	2750	P235 GH	P235 GH	14,060	In combination with drum V-102	Designed for DP=20mbar
E-103	Flue gas boiler	Flue gas (TS)	Water / Steam (SS)	BXM	1	1	1	2565	530	19.05	3200	1580	3200	P235 GH	P235 GH	22,740	In combination with drum V-103	Designed for DP=20mbar
E-104	Flue gas boiler	Flue gas (TS)	Water / Steam (SS)	BXM	1	1	1	1630	228	19.05	3350	1000	3350	P235 GH	P235 GH	9,970	In combination with drum V-104	Designed for DP=20mbar
E-105	Flue gas boiler	Flue gas (TS)	Water / Steam (SS)	BXM	1	1	1	2230	412	19.05	3200	1380	3200	P235 GH	P235 GH	16,361	In combination with drum V-105	Designed for DP=20mbar
E-106A	Flue gas boiler A	Flue gas (TS)	Water / Steam (SS)	BXM	1	1	1	2131	537	19.05	2700	1730	2700	P235 GH	P235 GH	23,850	In combination with drum V-106A	Designed for DP=20mbar
E-106B	Flue gas boiler B	Flue gas (TS)	Water / Steam (SS)	BXM	1	1	1	2131	537	19.05	2700	1730	2700	P235 GH	P235 GH	23,850	In combination with drum V-106B	Designed for DP=20mbar
E-107	Flue gas boiler	Flue gas (TS)	Water / Steam (SS)	BXM	1	1	1	3443	706	19.05	3150	1830	3150	P235 GH	P235 GH	29,412	In combination with drum V-107	Designed for DP=20mbar
E-108	Flue gas boiler	Flue gas (TS)	Water / Steam (SS)	BXM	1	1	1	1516	178	19.05	3600	850	3600	P235 GH	P235 GH	6,800	In combination with drum V-108	Designed for DP=20mbar
E-109	Flue gas boiler	Flue gas (TS)	Water / Steam (SS)	BXM	1	1	1	248	62	19.05	2550	600	2550	P235 GH	P235 GH	2,600	In combination with drum V-109	Designed for DP=20mbar
E-110A	Flue gas boiler A	Flue gas (TS)	Water / Steam (SS)	BXM	1	1	1	104	42	19.05	1350	700	1350	P235 GH	P235 GH	2,500	In combination with drum V-110	Designed for DP=20mbar
E-110B	Flue gas boiler B	Flue gas (TS)	Water / Steam (SS)	BXM	1	1	1	104	42	19.05	1350	700	1350	P235 GH	P235 GH	2,500	In combination with drum V-110	Designed for DP=20mbar
E-116A	Stripper reboiler	LP steam	Amine	BKU	1	1	1	12225	1650	19.05	5850	1700 / 2200	5850	SS304	SS304	50,680		
E-116B	Stripper reboiler	LP steam	Amine	BKU	1	1	1	12225	1650	19.05	5850	1700 / 2200	5850	SS304	SS304	50,680		

Table 3.11.4. Heat Exchanger summary (S&T) HS3 Case A

Heat exchanger summary **HS3 Case A**

Summary

Plate and Frame

Tag. No.	Service	Medium hot side	Medium cold side	Type	Quantity	Parallel	In series	Duty, kW	Heat transfer area , m2	Material of Construction Shell or Headers	Material of Construction Tubes or Plates	Remarks
E-111	DCC / FGS water cooler	Process water	Cooling water	Plate & Frame	1	1	1	25400	900	SS316	SS316	Heat transfer area based on typical heat transfer coefficient for this application
E-112	Amine cooler	Lean Amine	Cooling water	Plate & Frame	1	1	1	7220	207	SS316	SS316	Heat transfer area based on typical heat transfer coefficient for this application
E-113	Combined amine cooler / heater	Lean amine	Rich amine	Plate & Frame	1	1	1	23806	2430	SS316	SS316	Heat transfer area based on typical heat transfer coefficient for this application
E-114	Absorber top cooler	Process water	Cooling water	Plate & Frame	1	1	1	10634	300	SS316	SS316	Heat transfer area based on typical heat transfer coefficient for this application
E-115	Stripper condenser / Gas cooler	CO_2 gas / water	Cooling water	Plate & Frame	1	1	1	6280	203	SS316	SS316	Heat transfer area based on typical heat transfer coefficient for this application

Table 3.11.5. Heat Exchanger summary (PFHE) HS3 Case A

Heat exchanger Summary Dry-cooler — **MEA Case A**

											Material of Construction		
Tag. No.	**Service**	**Medium hot side**	**Medium cold side**	**Type**	**Quantity**	**Parallel**	**In series**	**Duty, kW**	**Estimated plot area, m2**	**Power consumption fans, kW**	**Tubes**	**Fins**	**Remarks**
E-401	Cooling water circulation cooler	Cooling water (20 wt% glycol)	Air	Aircooler	1	1	1	47,275	1200	1882	CS	Galvanized steel	Anticipated aircooler width = 12-16 m

Table 3.11.6. Heat Exchanger summary sheet (Dry-cooler) HS3 Case A

Pump Summary	HS3 Case A										
									Material of Construction		
Tag. No.	Service	Type	Quantity	Design flowrate, m3/hr	Fluid density, kg/m3	Diff. head @ design flowrate, bar	Estimated absorbed power, kW	Installed power, kW	Casing	Impeller	Remarks
P-101A	Flue gas scrubber circ. pump	Centrifugal	1	500	1000	2	35	45	SS316	SS316	50% capacity
P-101B	Flue gas scrubber circ. pump	Centrifugal	1	500	1000	2	35	45	SS316	SS316	50% capacity
P-101S	Flue gas scrubber circ. pump	Centrifugal	1	500	1000	2	35	45	SS316	SS316	Spare pump
P-102A	Rich amine pump	Centrifugal	1	225	1100	2.5	20	25	SS316	SS316	50% capacity
P-102B	Rich amine pump	Centrifugal	1	225	1100	2.5	20	25	SS316	SS316	50% capacity
P-102S	Rich amine pump	Centrifugal	1	225	1100	2.5	20	25	SS316	SS316	Spare pump
P-103A	Lean amine pump	Centrifugal	1	210	1000	3.2	23	30	SS316	SS316	50% capacity
P-103B	Lean amine pump	Centrifugal	1	210	1000	3.2	23	30	SS316	SS316	50% capacity
P-103S	Lean amine pump	Centrifugal	1	210	1000	3.2	23	30	SS316	SS316	Spare pump
P-104A	Wash water circ. Pump	Centrifugal	1	225	1000	2.5	20	25	SS316	SS316	50% capacity
P-104B	Wash water circ. Pump	Centrifugal	1	225	1000	2.5	20	25	SS316	SS316	50% capacity
P-104S	Wash water circ. Pump	Centrifugal	1	225	1000	2.5	20	25	SS316	SS316	Spare pump
P-105A	Stripper reflux pump	Centrifugal	1	8	1000	1.7	0.6	0.75	SS316	SS316	100% capacity
P-105S	Stripper reflux pump	Centrifugal	1	8	1000	1.7	0.6	0.75	SS316	SS316	Spare pump
P-120A	Condensate feed pump	Centrifugal	1	40.5	1000	2.5	3.5	4.5	Cast Iron	Cast Iron	100% capacity
P-120S	Condensate feed pump	Centrifugal	1	40.5	1000	2.5	3.5	4.5	Cast Iron	Cast Iron	Spare pump
P-121A	Condensate return pump	Centrifugal	1	N.A.	N.A.	N.A.	N.A.		Cast Iron	Cast Iron	Not applicable
P-121S	Condensate return pump	Centrifugal	1	N.A.	N.A.	N.A.	N.A.		Cast Iron	Cast Iron	Not applicable
P-401A	cooling water pump	Centrifugal	1	950	1000	2.5	82.5	100	Cast Iron	Cast Iron	33.3% capacity
P-401B	cooling water pump	Centrifugal	1	950	1000	2.5	82.5	100	Cast Iron	Cast Iron	33.3% capacity
P-401C	cooling water pump	Centrifugal	1	950	1000	2.5	82.5	100	Cast Iron	Cast Iron	33.3% capacity
P-401S	cooling water pump (spare)	Centrifugal	1	950	1000	2.5	82.5	100	Cast Iron	Cast Iron	33.3% capacity

Table 3.11.7. Pump summary sheet HS3 Case A

Package Unit Summary	HS3 Case A			
Tag. No.	**Service**	**Capacity / Duty**	**Estimated plot (LxWxH), m**	**Remarks**
X-101	Natural gas fired boiler unit	10700 kg/h LP steam production	7050 x 3375 x 3875	NG consumption = 695 Nm3/h
X-102	Amine reclaimer unit	150 kg/h		Estimated from expected amine solvent make-up
X-103	Amine solvent supply system	15 kg/h average		
X-103	Initial HS3 solvent filling (45 wt%)	140 m3		

Table 3.11.8. Package unit summary sheet HS3 Case A

4 Equipment Capital Cost Estimation method and cost summary sheets

4.1 Introduction

The basis for the equipment cost estimations are the equipment summary sheets as presented in Chapter 3. The used sources for estimation of the delivered costs of individual process equipment for this demonstration project are:

- DACE Price booklet edition 36. [DACE Price Booklet | Independent cost estimate data for the process industry]
- In-house costing data
- Recent vendor quotations

The budget prices quoted in the DACE price booklet have been established based on the assessment of actual costs of recently finished projects. The data is based on West-European construction method and cost data are based on the Netherlands. The cost data is based on 1st quarter of 2023.

For process equipment for which no cost data is available from the DACE price booklet, vendor budget quotes will be used. For each type of equipment, the costing basis and costing method will be discussed in the following sections.

As mentioned in Chapter 3, the Case A scenarios are the design cases for the equipment in the CO_2 capture plant since they process the largest amounts of flue gas compared to the B cases.

The cost for the equipment for the B cases are estimated by means of the so-called six-tenth factor principle:

$$E_b = E_a \left(\frac{c_b}{c_a} \right)^{0.6}$$

where,
ca = Capacity of equipment a
cb = Capacity of equipment b
Ea = Purchased cost of equipment a
Eb = Purchased cost of equipment b

According to this rule, if the cost of a given unit
at one capacity is known, the cost of a similar unit with X times the capacity of the first, is approximately X^0.6 times the cost of the initial unit.

The exponent depends largely on where you are on the equipment costing curve as can be seen from the equipment cost graphs in this chapter. The exponent can reach 1 for very large process scales as can be seen from the costing graphs.

Section 4.11 provides the equipment cost summary sheets for MEA and HS3 Case A.

The equipment costs for MEA and HS3 Case B will be calculated as part of the Total Plant Cost calculations as discussed in Chapter 6.

4.2 Flue gas fan / booster

No costing data available from DACE booklet.

Vendor quotation received for budget pricing.

4.3 Columns

The DACE price booklet is used for the cost estimation of the bare columns i.e., the column shell including skirt, manholes and process nozzles but excluding the internals.

Figure 4.3.1. shows the costing graph for the selected material SS304 for the columns as function of bare column weight as explained above.

The last data point in Dace is a weight of 106 MT. But it can be seen from the graph that for large column weights the relation between weight and cost becomes linear.

For the Absorber column with an estimated weight of ca. 150 MT for HS3 Case A the extrapolated price is used based on this linear relationship. This price has been cross-reference checked with the quoted price from the Pentair approved pressure vessel vendor corrected for the location factor.

The cost for the required column internals per column, like liquid distributors draw-off trays, packing material etc. as specified in the column summary sheets has been estimated by a dedicated column internals vendor.

The estimated bare column and column internals prices are summarized in sections 4.10 and 4.11.

Prices for the bare columns include X-ray and inspection. Platforms, cage ladders, transport are excluded from the price.

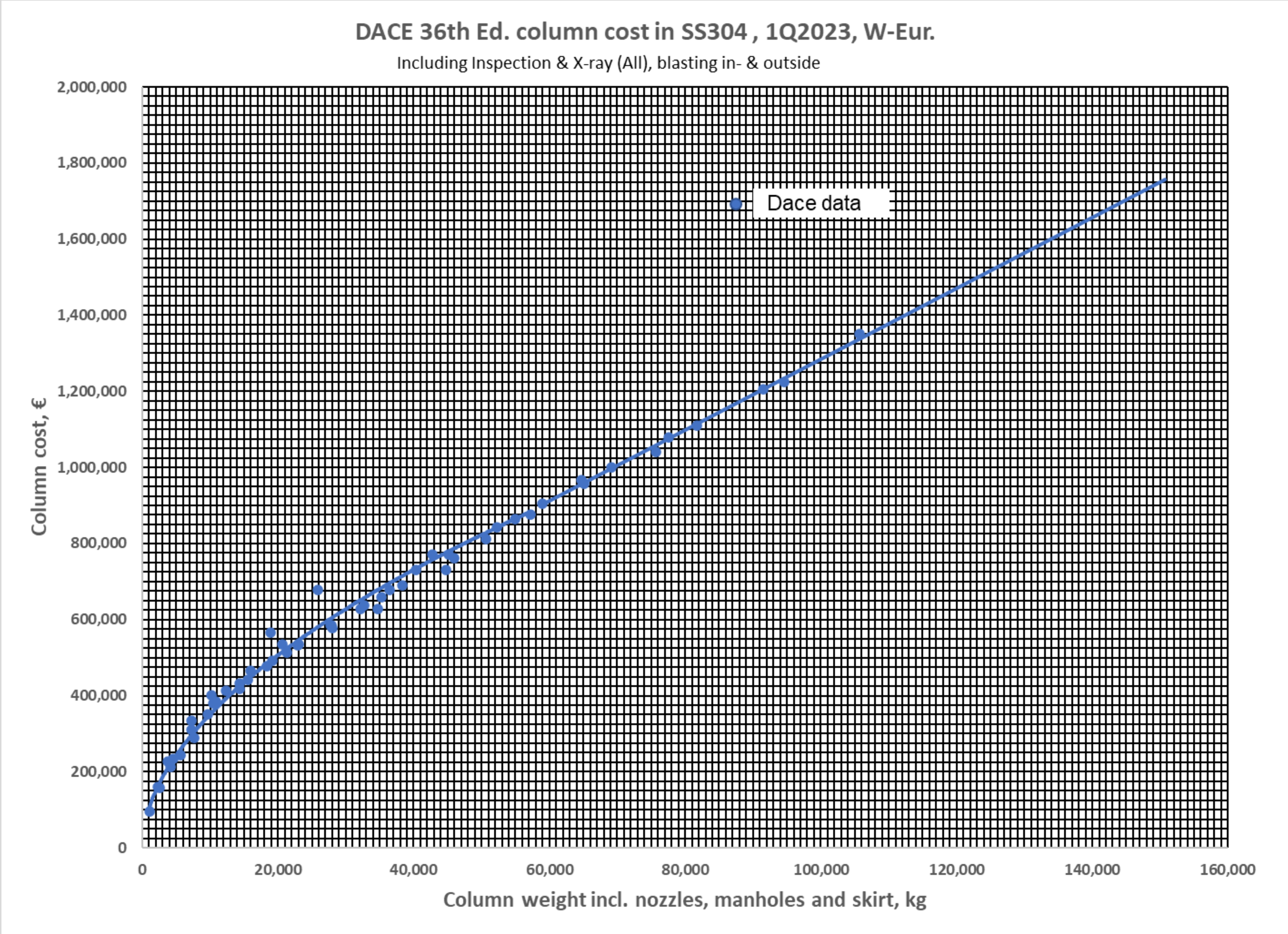


Figure 4.3.1. Column cost – SS304

4.4 Vessels / Drums

The pricing data from the DACE price booklet is used for estimating the process vessel cost based on the estimated weight and material of the process vessels / drums. Also, the vessel wall thickness is taken into account in the pricing. Hemispherical heads are considered for the vessels.
The cost curve for CS material can be seen in figure 4.4.1 and for SS304 material in figure 4.4.2.
The following items are included in the cost price:

- Supports
- X-ray
- Inspection
- Blasting in- and outside
- 1 Manhole
- Maximum 9 nozzles
- Painting outside
- Reinforcement rings if necessary

Heat treatment is excluded from the price.

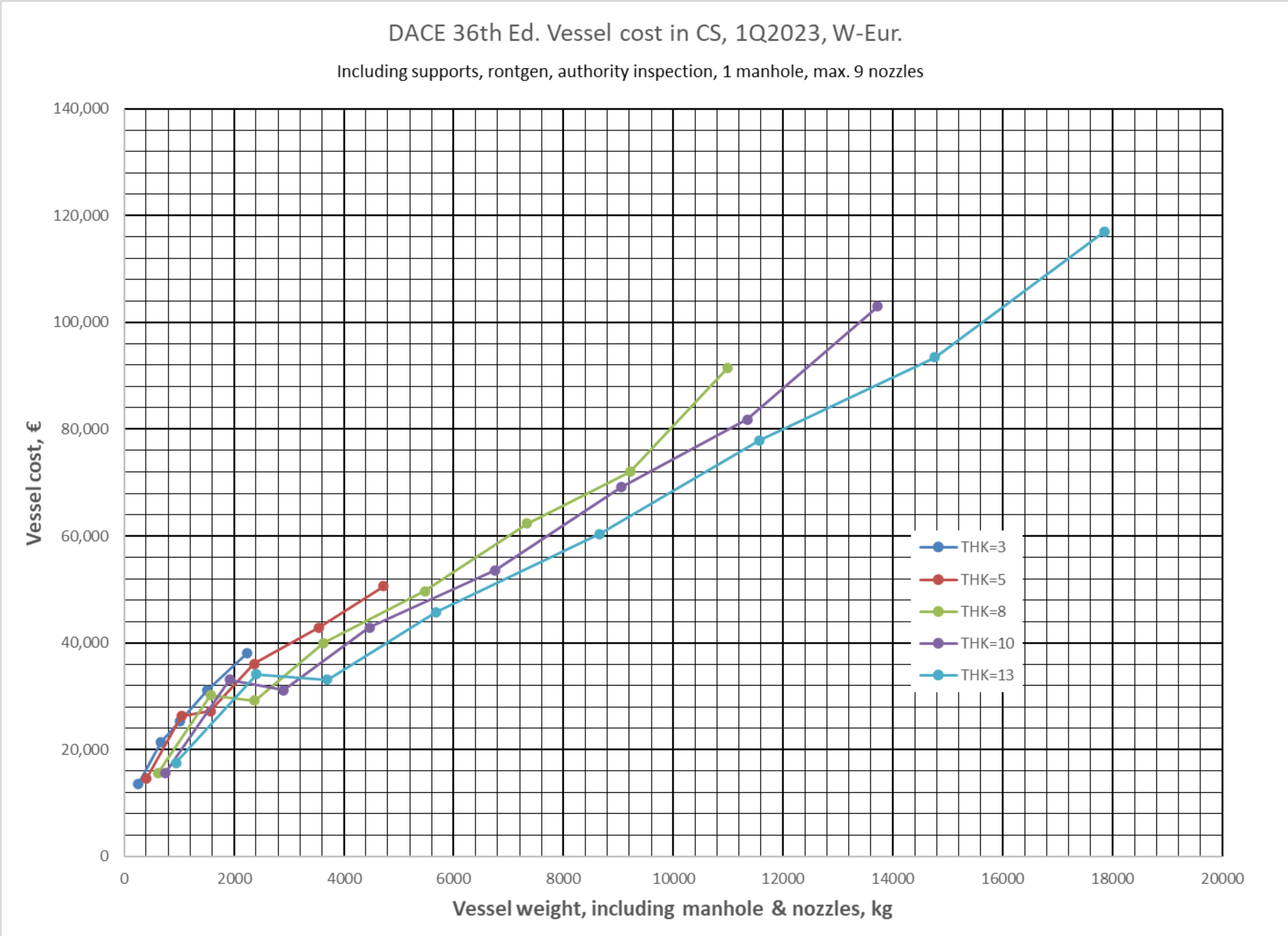


Figure 4.4.1. Vessel cost at various wall thicknesses – CS material

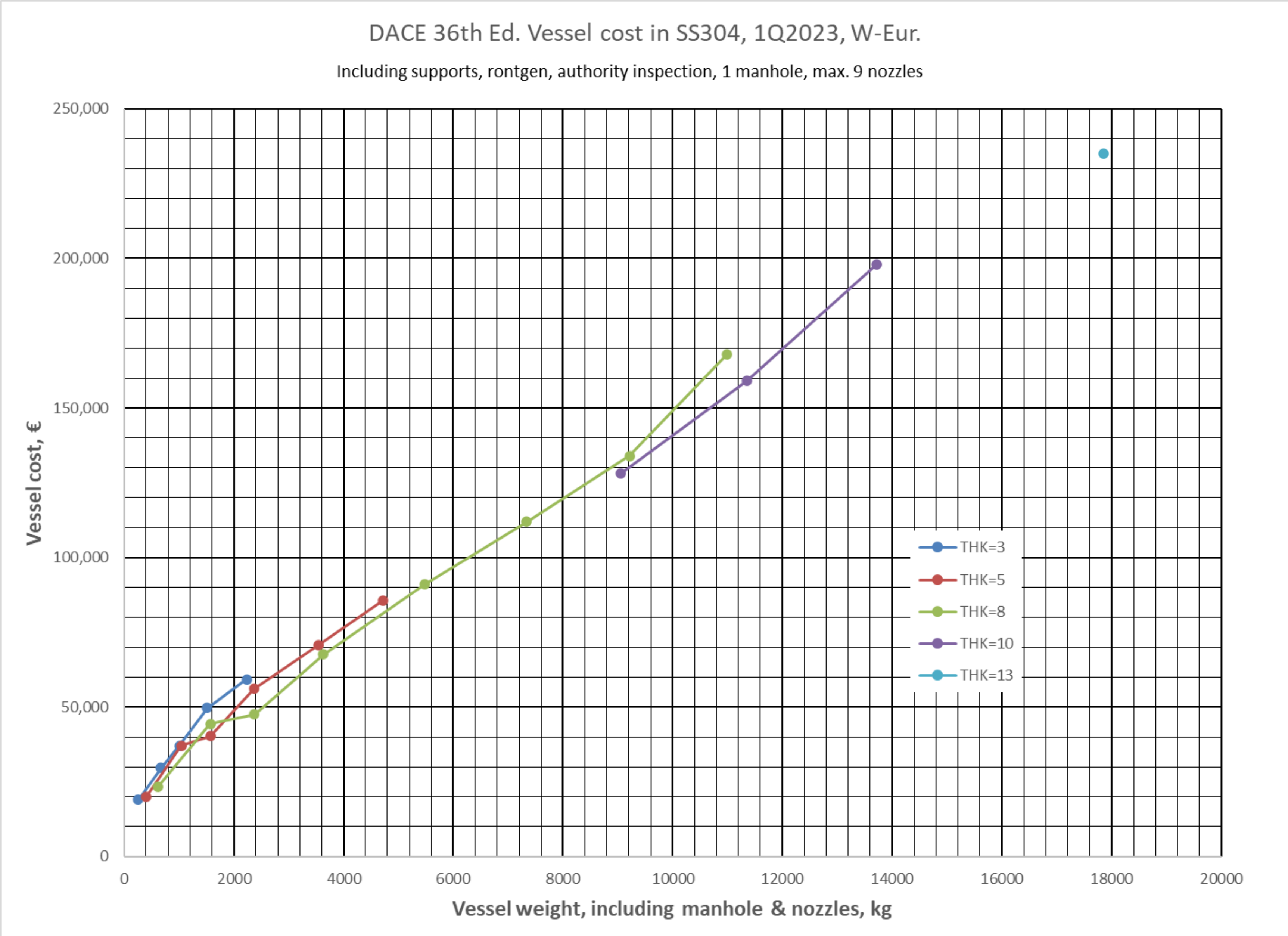


Figure 4.4.2. Vessel cost at various wall thicknesses– SS304 material

4.5 Heat Exchangers

Price data from the DACE price booklet is used for estimation of the cost for Shell & Tube (S&T) and Plate & Frame heat exchangers (PFHE) as listed in section 3.4.
The basis for costing of the shell & tube heat exchangers is the estimated weight as calculated from the Aspen EDR program.

For the plate & frame heat exchangers the total estimated plate surface area is used as the costing basis. Packing and compression bolts are included in the price.

Since there is no pricing data for dry-coolers in the DACE booklet, vendor quotations have been requested for the design and costing of the cooling water dry-cooler.

Figure 4.5.1 and 4.5.2 shows the weight specific cost curves for respective the CS and SS304 shell and tube heat exchangers.

The weight of each of the stripper reboilers i.e. ca. 33 ton, is outside the cost range listed in the DACE booklet. But it can be seen from the weight specific costing graphs that for large heat exchanger weights the drop in the weight specific cost becomes very small.
Therefore, for the kettle-type reboilers a specific cost of €16/kg is used which is the same as for the highest available weight S&T heat exchanger in DACE i.e. 20 ton.

The surface area specific cost curve for SS316 plate & frame heat exchangers in shown in figure 4.5.3.
The DACE price data goes up to a total surface area of 300 m2. It is assumed that for larger surface areas, the specific cost will remain constant i.e. ca. €260/m2.
The combined amine cooler / heater (E-113) for the HS3 Case A has an estimated total surface area of 2430 m2.

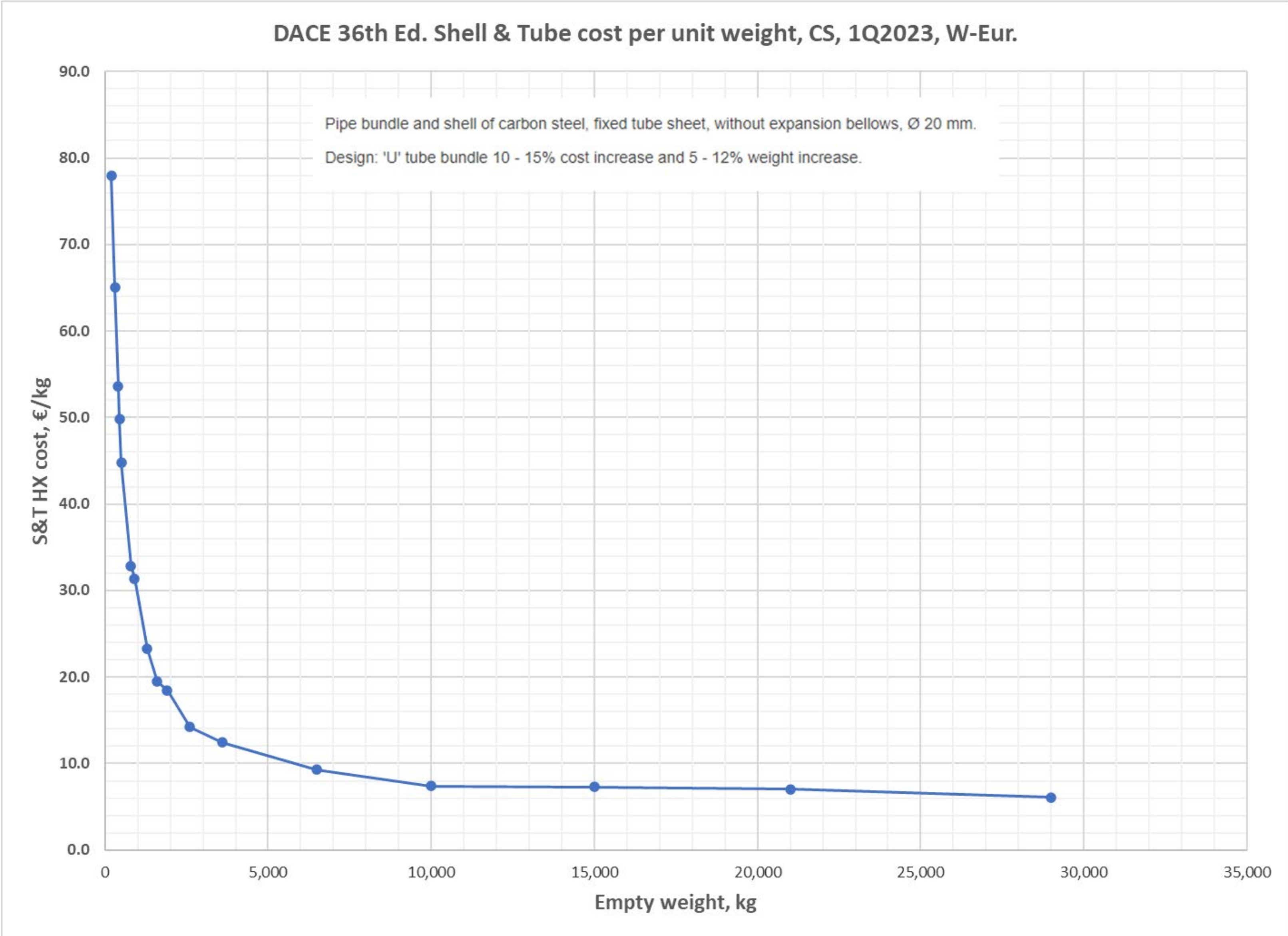


Figure 4.5.1. Shell & Tube heat exchanger cost – CS material

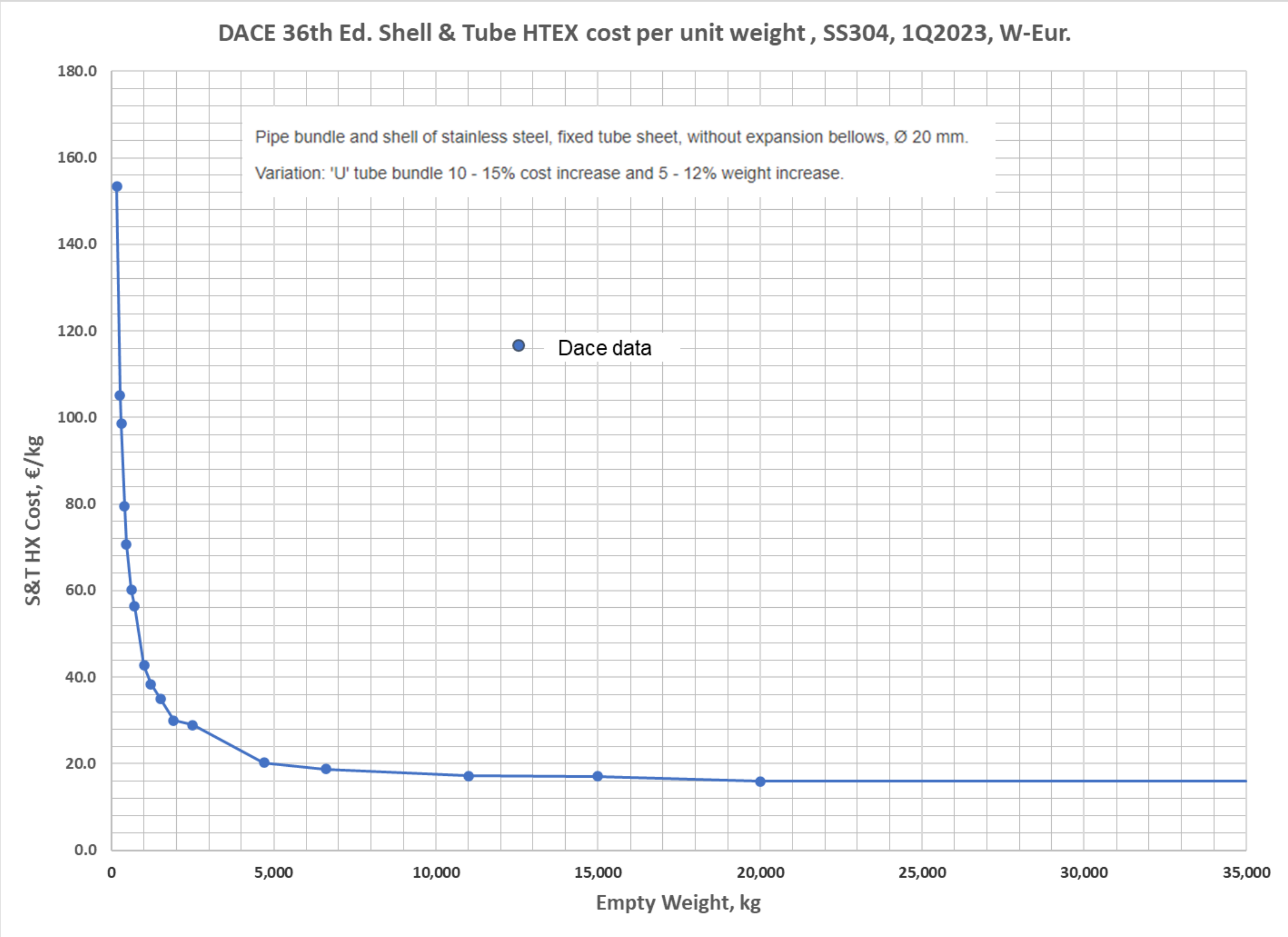


Figure 4.5.2. Shell & Tube heat exchanger cost – SS304 material

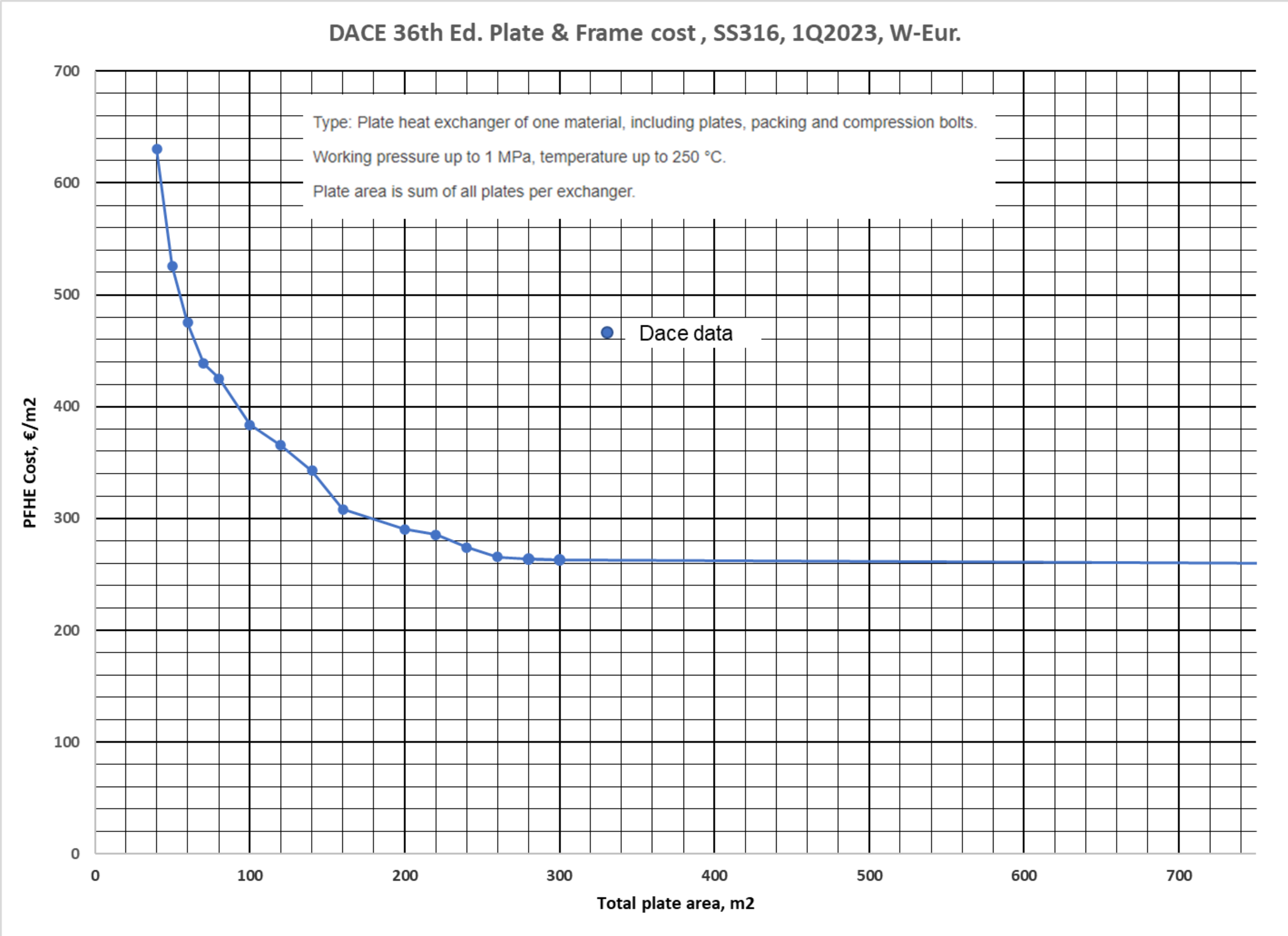


Figure 4.5.3. SS316 Plate & Frame heat exchanger specific cost

4.6 Pumps

Price data from the DACE price booklet will be used as function of capacity and required pump head. As mentioned in section 3.5, horizontal, single-stage, single suction pumps with volute are considered in the specified services. The rotational speed of the pumps is considered 1450 rpm. The pump cost includes a baseplate, mechanical sealing, foundation plate, coupling, a single mechanical seal and assembly cost.

The pump cost curves for cast iron and SS316 pumps is shown in respective figure 4.6.1 and 4.6.2 as function of capacity and pump head.

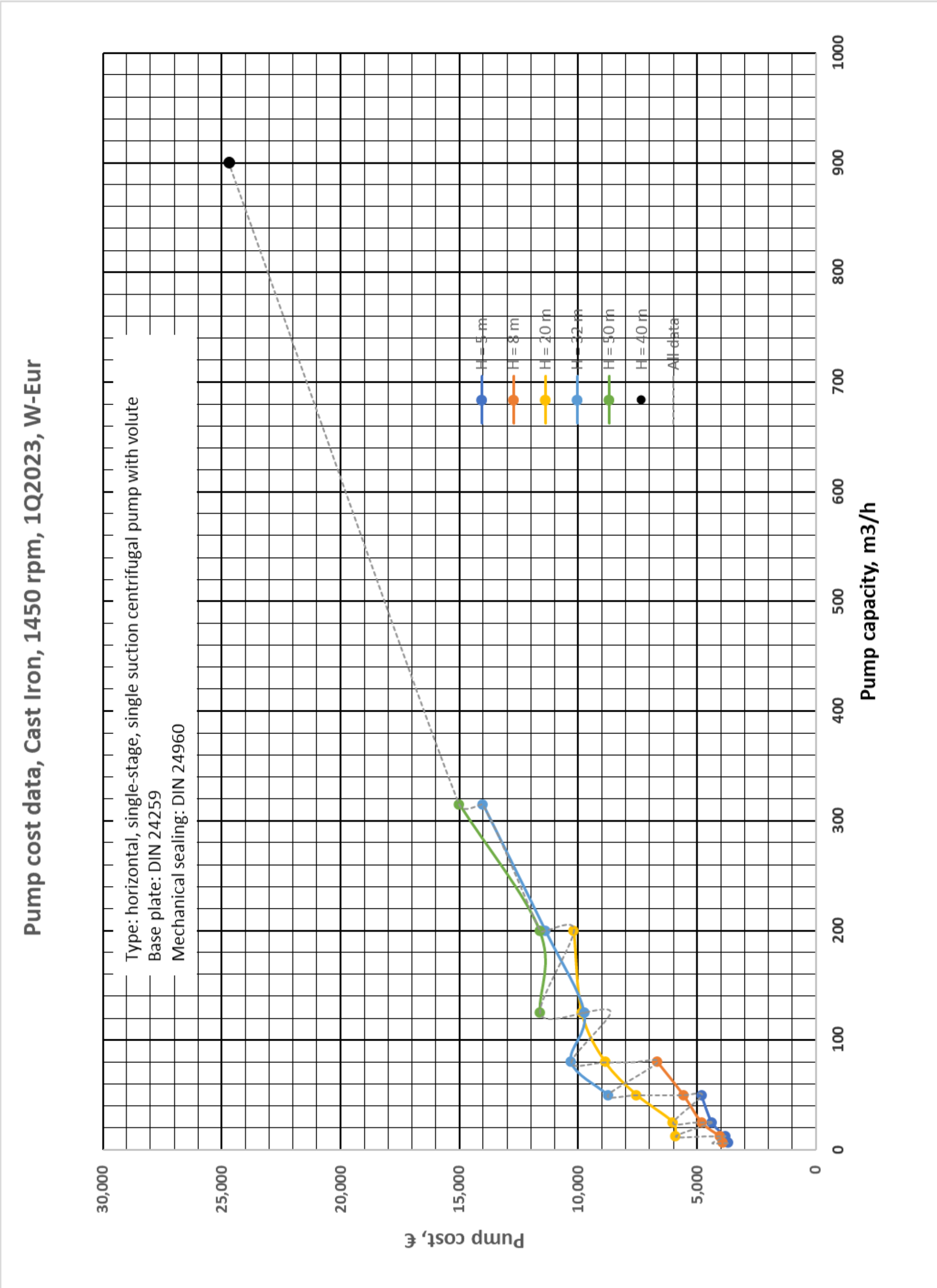


Figure 4.6.1. Cast Iron Pump costs.

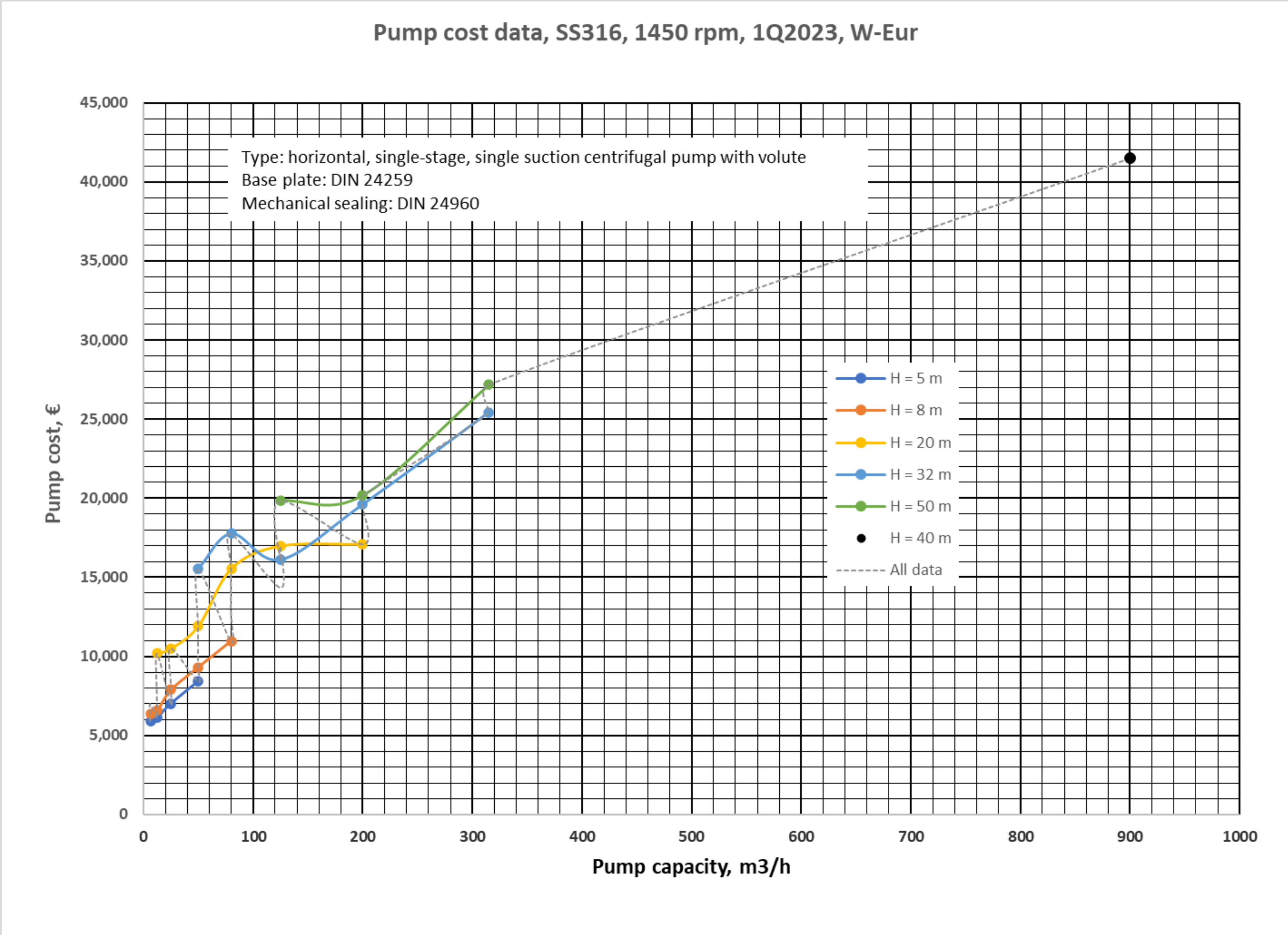


Figure 4.6.2. SS316 Pump costs.

4.7 Low voltage motor

The following Low voltage motors are considered for driving the flue gas fans, pumps and dry-cooler fans:

Type :Horizontal baseplate construction B3 (230 – 690, 50Hz, 3-phases)

Speed: 3000 rpm (2 poles)

Class: standard, EEx e

Protection class: IP55, fully closed

Insulation class: F

The Low voltage motor cost curve is shown in figure 4.7.1.

Cost data beyond 55 kW is extrapolated.

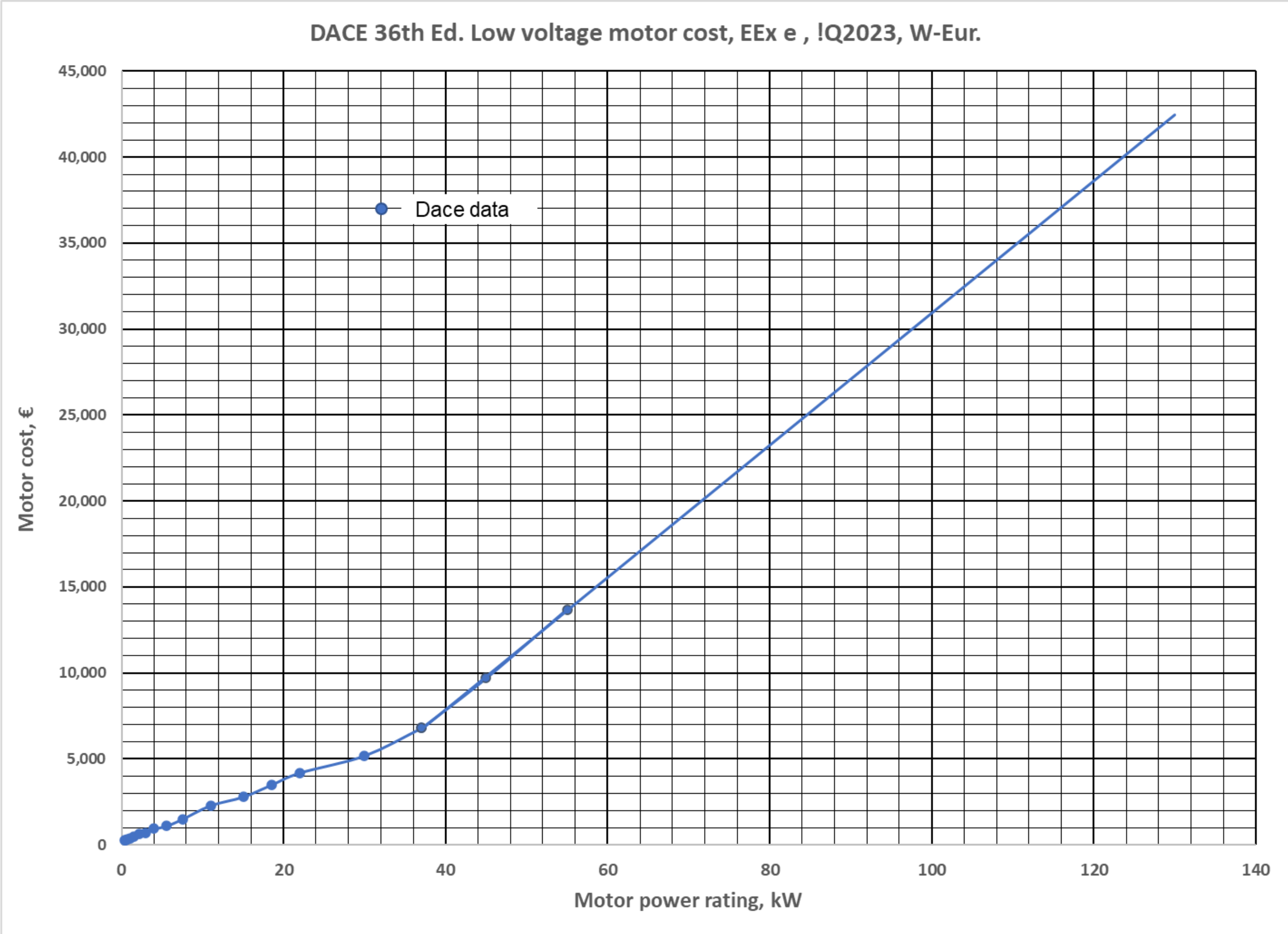


Figure 4.7.1. Low voltage motor costs.

4.8 Fired boiler package unit

No relevant price data is available from the DACE price booklet for the natural gas fired steam boiler system (X-101).
Therefor a quotation has been secured from a Pentair approved vendor for a budget price for the burner/boiler system.

4.9 Amine reclaimer package unit

In-house cost data is used for the cost estimation of a thermal amine reclaimer package unit part of the CO_2 capture plant. The cost is based on the expected amine consumption.

4.10 Flue gas ducting

The cost for the flue gas ducting is considered as part of the installation costs of the flue gas boiler system, DCC column and Absorber system as described in chapter 6

4.11 Equipment cost summary MEA Case A

Equipment costing summary sheet								
MEA Case A								
Tag. No.	Item / type	Service	Material	Costing method	DACE Costing parameter	Value	Unit	Cost, k€
A-101	Column vessel	Direct Contact Cooler column	SS304	DACE booklet	Weight	79,500	kg	1,100.00
A-101	Column Internals	Direct Contact Cooler column	SS304	Vendor quote	--		--	170.00
A-102	Column vessel	Absorber column	SS304	DACE booklet	Weight	120,000	kg	1,475.00
A-102	Column Internals	Absorber column	SS304	Vendor quote	--		--	850.00
A-103	Column vessel	Stripper column	SS304	DACE booklet	Weight	60,500	kg	900.00
A-103	Column Internals	Stripper column	SS304	Vendor quote	--		--	240.00
C-101A	Centrifugal blower	Flue gas booster	SS304	Vendor quote	--		--	75.30
C-101B	Centrifugal blower	Flue gas booster	SS304	Vendor quote	--		--	75.30
C-101C	Centrifugal blower	Flue gas booster	SS304	Vendor quote	--		--	75.30
V-101	Process vessel	steam / condensate drum	CS	DACE booklet	Weight	1,460	kg	27.74
V-101	Internals	Separators / distributors	CS	In-house data				4.16
V-102	Process vessel	steam / condensate drum	CS	DACE booklet	Weight	1,640	kg	29.52
V-102	Internals	Separators / distributors	CS	In-house data				4.43
V-103	Process vessel	steam / condensate drum	CS	DACE booklet	Weight	2,150	kg	36.55
V-103	Internals	Separators / distributors	CS	In-house data				5.48
V-104	Process vessel	steam / condensate drum	CS	DACE booklet	Weight	1,520	kg	28.12
V-104	Internals	Separators / distributors	CS	In-house data				4.22
V-105	Process vessel	steam / condensate drum	CS	DACE booklet	Weight	1,880	kg	31.96
V-105	Internals	Separators / distributors	CS	In-house data				4.79
V-106A	Process vessel	steam / condensate drum	CS	DACE booklet	Weight	2,140	kg	36.38
V-106A	Internals	Separators / distributors	CS	In-house data				5.46
V-106B	Process vessel	steam / condensate drum	CS	DACE booklet	Weight	2,140	kg	36.38
V-106B	Internals	Separators / distributors	CS	In-house data				5.46
V-107	Process vessel	steam / condensate drum	CS	DACE booklet	Weight	2,440	kg	34.16
V-107	Internals	Separators / distributors	CS	In-house data				5.12
V-108	Process vessel	steam / condensate drum	CS	DACE booklet	Weight	1,410	kg	26.79
V-108	Internals	Separators / distributors	CS	In-house data				4.02
V-109	Process vessel	steam / condensate drum	CS	DACE booklet	Weight	1,020	kg	24.48
V-109	Internals	Separators / distributors	CS	In-house data				3.67
V-110A	Process vessel	steam / condensate drum	CS	DACE booklet	Weight	980	kg	23.52
V-110A	Internals	Separators / distributors	CS	In-house data				3.53
V-110B	Process vessel	steam / condensate drum	CS	DACE booklet	Weight	980	kg	23.52
V-110B	Internals	Separators / distributors	CS	In-house data				3.53
F-101A-1	Process vessel	Amine solvent AC filter	SS304	DACE booklet	Weight	3,700	kg	68.82
F-101A-1	Activated carbon	Amine solvent AC filter	SS304	In-house data	Weight	6,050	kg	25.00
F-101A-2	Vessel + filling	Amine solvent particle filter	SS304	In-house data				48.17
F-102A-1	Process vessel	Amine solvent AC filter	SS304	DACE booklet	Weight	3,700	kg	68.82
F-102A-1	Activated carbon	Amine solvent AC filter	SS304	In-house data	Weight	6,050	kg	25.00
F-102A-2	Vessel + filling	Amine solvent particle filter	SS304	In-house data				48.17
V-112	Vessel	Stripper reflux drum	SS304	DACE booklet	Weight	2,400	kg	52.80
V-121	Vessel	Condensate feed / flash tank	CS	DACE booklet	Weight	2,400	kg	36.00
E-101	S&T heat exchanger	Flue gas boiler	P235 GH	DACE booklet	Weight	7,145	kg	70.74
E-102	S&T heat exchanger	Flue gas boiler	P235 GH	DACE booklet	Weight	14,060	kg	102.64
E-103	S&T heat exchanger	Flue gas boiler	P235 GH	DACE booklet	Weight	22,740	kg	159.18
E-104	S&T heat exchanger	Flue gas boiler	P235 GH	DACE booklet	Weight	9,970	kg	73.78
E-105	S&T heat exchanger	Flue gas boiler	P235 GH	DACE booklet	Weight	16,361	kg	116.16
E-106A	S&T heat exchanger	Flue gas boiler	P235 GH	DACE booklet	Weight	23,850	kg	166.95
E-106B	S&T heat exchanger	Flue gas boiler	P235 GH	DACE booklet	Weight	23,850	kg	166.95
E-107	S&T heat exchanger	Flue gas boiler	P235 GH	DACE booklet	Weight	29,412	kg	176.47
E-108	S&T heat exchanger	Flue gas boiler	P235 GH	DACE booklet	Weight	6,800	kg	62.56
E-109	S&T heat exchanger	Flue gas boiler	P235 GH	DACE booklet	Weight	2,600	kg	36.92
E-110A	S&T heat exchanger	Flue gas boiler	P235 GH	DACE booklet	Weight	2,500	kg	36.00
E-110B	S&T heat exchanger	Flue gas boiler	P235 GH	DACE booklet	Weight	2,500	kg	36.00
E-116A	S&T heat exchanger	Stripper reboiler	SS304	DACE booklet	Weight	33,383	kg	534.13
E-116B	S&T heat exchanger	Stripper reboiler	SS304	DACE booklet	Weight	33,383	kg	534.13
E-111	Plate&Frame HX	DCC circulation cooler	SS316	DACE booklet	Surface area	900	m2	234.00
E-112	Plate&Frame HX	Amine cooler	SS316	DACE booklet	Surface area	137	m2	47.35
E-113	Plate&Frame HX	Combined amine cooler / heater	SS316	DACE booklet	Surface area	1,466	m2	381.16
E-114	Plate&Frame HX	Absorber wash water cooler	SS316	DACE booklet	Surface area	415	m2	107.90
E-115	Plate&Frame HX	Stripper condenser	SS316	DACE booklet	Surface area	223	m2	62.93
E-401	Dry-cooler	Cooling water cooler	Cast Iron	Vendor quote				4,600.00

Equipment costing summary sheet								
MEA Case A								
Tag. No.	**Item / type**	**Service**	**Material**	**Costing method**	**DACE Costing parameter**	**Value**	**Unit**	**Cost, k€**
P-101A	Centrifugal pump	DCC circulation pump	SS316	DACE booklet	Flow & head	500, 20	m3/h, m	33.50
P-101B	Centrifugal pump	DCC circulation pump	SS316	DACE booklet	Flow & head	500, 20	m3/h, m	33.50
P-101S	Centrifugal pump	DCC circulation pump	SS316	DACE booklet	Flow & head	500, 20	m3/h, m	33.50
P-102A	Centrifugal pump	Rich amine pump	SS316	DACE booklet	Flow & head	300, 25	m3/h, m	25.00
P-102B	Centrifugal pump	Rich amine pump	SS316	DACE booklet	Flow & head	300, 25	m3/h, m	25.00
P-102S	Centrifugal pump	Rich amine pump	SS316	DACE booklet	Flow & head	300, 25	m3/h, m	25.00
P-103A	Centrifugal pump	Lean amine pump	SS316	DACE booklet	Flow & head	275, 32	m3/h, m	23.00
P-103B	Centrifugal pump	Lean amine pump	SS316	DACE booklet	Flow & head	275, 32	m3/h, m	23.00
P-103S	Centrifugal pump	Lean amine pump	SS316	DACE booklet	Flow & head	275, 32	m3/h, m	23.00
P-104A	Centrifugal pump	Wash water pump	SS316	DACE booklet	Flow & head	350, 25	m3/h, m	28.00
P-104B	Centrifugal pump	Wash water pump	SS316	DACE booklet	Flow & head	350, 25	m3/h, m	28.00
P-104S	Centrifugal pump	Wash water pump	SS316	DACE booklet	Flow & head	350, 25	m3/h, m	28.00
P-105A	Centrifugal pump	Stripper reflux pump	SS316	DACE booklet	Flow & head	15,17	m3/h, m	6.50
P-105S	Centrifugal pump	Stripper reflux pump	SS316	DACE booklet	Flow & head	15,17	m3/h, m	6.50
P-120/121A	Centrifugal pump	Steam condensate pump	Cast Iron	DACE booklet	Flow & head	55, 25	m3/h, m	13.00
P-120/121S	Centrifugal pump	Steam condensate pump	Cast Iron	DACE booklet	Flow & head	55, 25	m3/h, m	13.00
P-401A	Centrifugal pump	Cooling water circulation pump	Cast Iron	DACE booklet	Flow & head	1200, 25	m3/h, m	27.50
P-401B	Centrifugal pump	Cooling water circulation pump	Cast Iron	DACE booklet	Flow & head	1200, 25	m3/h, m	27.50
P-401C	Centrifugal pump	Cooling water circulation pump	Cast Iron	DACE booklet	Flow & head	1200, 25	m3/h, m	27.50
P-401D	Centrifugal pump	Cooling water circulation pump	Cast Iron	DACE booklet	Flow & head	1200, 25	m3/h, m	27.50
PM-101A	Pump motor	DCC circulation pump		DACE booklet	Inst. Power	45	kW	9.60
PM-101B	Pump motor	DCC circulation pump		DACE booklet	Inst. Power	45	kW	9.60
PM-101S	Pump motor	DCC circulation pump		DACE booklet	Inst. Power	45	kW	9.60
PM-102A	Pump motor	Rich amine pump		DACE booklet	Inst. Power	30	kW	5.30
PM-102B	Pump motor	Rich amine pump		DACE booklet	Inst. Power	30	kW	5.30
PM-102S	Pump motor	Rich amine pump		DACE booklet	Inst. Power	30	kW	5.30
PM-103A	Pump motor	Lean amine pump		DACE booklet	Inst. Power	40	kW	6.80
PM-103B	Pump motor	Lean amine pump		DACE booklet	Inst. Power	40	kW	6.80
PM-103S	Pump motor	Lean amine pump		DACE booklet	Inst. Power	40	kW	6.80
PM-104A	Pump motor	Wash water pump		DACE booklet	Inst. Power	45	kW	9.60
PM-104B	Pump motor	Wash water pump		DACE booklet	Inst. Power	45	kW	9.60
PM-104S	Pump motor	Wash water pump		DACE booklet	Inst. Power	45	kW	9.60
PM-105A	Pump motor	Stripper reflux pump		DACE booklet	Inst. Power	1	kW	0.38
PM-105S	Pump motor	Stripper reflux pump		DACE booklet	Inst. Power	1	kW	0.38
PM-120/121A	Pump motor	Steam condensate pump		DACE booklet	Inst. Power	6	kW	1.15
PM-120/121S	Pump motor	Steam condensate pump		DACE booklet	Inst. Power	6	kW	1.15
PM-401A	Pump motor	Cooling water circulation pump		DACE booklet	Inst. Power	130	kW	42.50
PM-401B	Pump motor	Cooling water circulation pump		DACE booklet	Inst. Power	130	kW	42.50
PM-401C	Pump motor	Cooling water circulation pump		DACE booklet	Inst. Power	130	kW	42.50
PM-401D	Pump motor	Cooling water circulation pump		DACE booklet	Inst. Power	130	kW	42.50
X-101	Package unit	Natural gas fired boiler system		Vendor quote				382.65
X-102	Package unit	Amine reclaimer unit	SS316	In-house data				335.00
X-103	Package unit	Amime solvent supply system	SS304	In-house data				20.00

4.12 Equipment cost summary HS3 Case A

Equipment costing summary sheet								
HS3 Case A								
Tag. No.	Item / type	Service	Material	Costing method	DACE Costing parameter	Value	Unit	Cost, k€
A-101	Column vessel	Direct Contact Cooler column	SS304	DACE booklet	Weight	79,500	kg	1,100.00
A-101	Column Internals	Direct Contact Cooler column	SS304	Vendor quote	--		--	170.00
A-102	Column vessel	Absorber column	SS304	DACE booklet	Weight	149,000	kg	1,737.50
A-102	Column Internals	Absorber column	SS304	Vendor quote	--		--	950.00
A-103	Column vessel	Stripper column	SS304	DACE booklet	Weight	42,500	kg	750.00
A-103	Column Internals	Stripper column	SS304	Vendor quote	--		--	280.00
C-101A	Centrifugal blower	Flue gas booster	SS304	Vendor quote	--		--	75.30
C-101B	Centrifugal blower	Flue gas booster	SS304	Vendor quote	--		--	75.30
C-101C	Centrifugal blower	Flue gas booster	SS304	Vendor quote	--		--	75.30
V-101	Process vessel	steam / condensate drum	CS	DACE booklet	Weight	1,460	kg	27.74
V-101	Internals	Separators / distributors	CS	In-house data				4.16
V-102	Process vessel	steam / condensate drum	CS	DACE booklet	Weight	1,640	kg	29.52
V-102	Internals	Separators / distributors	CS	In-house data				4.43
V-103	Process vessel	steam / condensate drum	CS	DACE booklet	Weight	2,150	kg	36.55
V-103	Internals	Separators / distributors	CS	In-house data				5.48
V-104	Process vessel	steam / condensate drum	CS	DACE booklet	Weight	1,520	kg	28.12
V-104	Internals	Separators / distributors	CS	In-house data				4.22
V-105	Process vessel	steam / condensate drum	CS	DACE booklet	Weight	1,880	kg	31.96
V-105	Internals	Separators / distributors	CS	In-house data				4.79
V-106A	Process vessel	steam / condensate drum	CS	DACE booklet	Weight	2,140	kg	36.38
V-106A	Internals	Separators / distributors	CS	In-house data				5.46
V-106B	Process vessel	steam / condensate drum	CS	DACE booklet	Weight	2,140	kg	36.38
V-106B	Internals	Separators / distributors	CS	In-house data				5.46
V-107	Process vessel	steam / condensate drum	CS	DACE booklet	Weight	2,440	kg	34.16
V-107	Internals	Separators / distributors	CS	In-house data				5.12
V-108	Process vessel	steam / condensate drum	CS	DACE booklet	Weight	1,410	kg	26.79
V-108	Internals	Separators / distributors	CS	In-house data				4.02
V-109	Process vessel	steam / condensate drum	CS	DACE booklet	Weight	1,020	kg	24.48
V-109	Internals	Separators / distributors	CS	In-house data				3.67
V-110A	Process vessel	steam / condensate drum	CS	DACE booklet	Weight	980	kg	23.52
V-110A	Internals	Separators / distributors	CS	In-house data				3.53
V-110B	Process vessel	steam / condensate drum	CS	DACE booklet	Weight	980	kg	23.52
V-110B	Internals	Separators / distributors	CS	In-house data				3.53
F-101A-1	Process vessel	Amine solvent AC filter	SS304	DACE booklet	Weight	3,060	kg	58.14
F-101A-1	Activated carbon	Amine solvent AC filter	SS304	In-house data	Weight	6,050	kg	19.00
F-101A-2	Vessel + filling	Amine solvent particle filter	SS304	In-house data				40.70
F-102A-1	Process vessel	Amine solvent AC filter	SS304	DACE booklet	Weight	3,700	kg	58.14
F-102A-1	Activated carbon	Amine solvent AC filter	SS304	In-house data	Weight	6,050	kg	19.00
F-102A-2	Vessel + filling	Amine solvent particle filter	SS304	In-house data				40.70
V-112	Vessel	Stripper reflux drum	SS304	DACE booklet	Weight	2,400	kg	52.80
V-121	Vessel	Condensate feed / flash tank	CS	DACE booklet	Weight	2,400	kg	31.84
E-101	S&T heat exchanger	Flue gas boiler	P235 GH	DACE booklet	Weight	7,145	kg	70.74
E-102	S&T heat exchanger	Flue gas boiler	P235 GH	DACE booklet	Weight	14,060	kg	102.64
E-103	S&T heat exchanger	Flue gas boiler	P235 GH	DACE booklet	Weight	22,740	kg	159.18
E-104	S&T heat exchanger	Flue gas boiler	P235 GH	DACE booklet	Weight	9,970	kg	73.78
E-105	S&T heat exchanger	Flue gas boiler	P235 GH	DACE booklet	Weight	16,361	kg	116.16
E-106A	S&T heat exchanger	Flue gas boiler	P235 GH	DACE booklet	Weight	23,850	kg	166.95
E-106B	S&T heat exchanger	Flue gas boiler	P235 GH	DACE booklet	Weight	23,850	kg	166.95
E-107	S&T heat exchanger	Flue gas boiler	P235 GH	DACE booklet	Weight	29,412	kg	176.47
E-108	S&T heat exchanger	Flue gas boiler	P235 GH	DACE booklet	Weight	6,800	kg	62.56
E-109	S&T heat exchanger	Flue gas boiler	P235 GH	DACE booklet	Weight	2,600	kg	36.92
E-110A	S&T heat exchanger	Flue gas boiler	P235 GH	DACE booklet	Weight	2,500	kg	36.00
E-110B	S&T heat exchanger	Flue gas boiler	P235 GH	DACE booklet	Weight	2,500	kg	36.00
E-116A	S&T heat exchanger	Stripper reboiler	SS304	DACE booklet	Weight	50,680	kg	534.13
E-116B	S&T heat exchanger	Stripper reboiler	SS304	DACE booklet	Weight	50,680	kg	534.13
E-111	Plate&Frame HX	DCC circulation cooler	SS316	DACE booklet	Surface area	900	m2	234.00
E-112	Plate&Frame HX	Amine cooler	SS316	DACE booklet	Surface area	207	m2	60.25
E-113	Plate&Frame HX	Combined amine cooler / heater	SS316	DACE booklet	Surface area	2,430	m2	631.80
E-114	Plate&Frame HX	Absorber wash water cooler	SS316	DACE booklet	Surface area	300	m2	78.00
E-115	Plate&Frame HX	Stripper condenser	SS316	DACE booklet	Surface area	203	m2	59.57
E-401	Dry-cooler	Cooling water cooler	Cast Iron	Vendor quote				4,300.00

Equipment costing summary sheet

HS3 Case A

Tag. No.	Item / type	Service	Material	Costing method	DACE Costing parameter	Value	Unit	Cost, k€
P-101A	Centrifugal pump	DCC circulation pump	SS316	DACE booklet	Flow & head	500, 20	m3/h, m	33.50
P-101B	Centrifugal pump	DCC circulation pump	SS316	DACE booklet	Flow & head	500, 20	m3/h, m	33.50
P-101S	Centrifugal pump	DCC circulation pump	SS316	DACE booklet	Flow & head	500, 20	m3/h, m	33.50
P-102A	Centrifugal pump	Rich amine pump	SS316	DACE booklet	Flow & head	225, 25	m3/h, m	20.50
P-102B	Centrifugal pump	Rich amine pump	SS316	DACE booklet	Flow & head	225, 25	m3/h, m	20.50
P-102S	Centrifugal pump	Rich amine pump	SS316	DACE booklet	Flow & head	225, 25	m3/h, m	20.50
P-103A	Centrifugal pump	Lean amine pump	SS316	DACE booklet	Flow & head	210, 32	m3/h, m	20.00
P-103B	Centrifugal pump	Lean amine pump	SS316	DACE booklet	Flow & head	210, 32	m3/h, m	20.00
P-103S	Centrifugal pump	Lean amine pump	SS316	DACE booklet	Flow & head	210, 32	m3/h, m	20.00
P-104A	Centrifugal pump	Wash water pump	SS316	DACE booklet	Flow & head	225, 25	m3/h, m	20.50
P-104B	Centrifugal pump	Wash water pump	SS316	DACE booklet	Flow & head	225, 25	m3/h, m	20.50
P-104S	Centrifugal pump	Wash water pump	SS316	DACE booklet	Flow & head	225, 25	m3/h, m	20.50
P-105A	Centrifugal pump	Stripper reflux pump	SS316	DACE booklet	Flow & head	8,17	m3/h, m	6.00
P-105S	Centrifugal pump	Stripper reflux pump	SS316	DACE booklet	Flow & head	8,17	m3/h, m	6.00
P-120/121A	Centrifugal pump	Steam condensate pump	Cast Iron	DACE booklet	Flow & head	40, 25	m3/h, m	12.00
P-120/121S	Centrifugal pump	Steam condensate pump	Cast Iron	DACE booklet	Flow & head	40, 25	m3/h, m	12.00
P-401A	Centrifugal pump	Cooling water circulation pump	Cast Iron	DACE booklet	Flow & head	950, 25	m3/h, m	25.50
P-401B	Centrifugal pump	Cooling water circulation pump	Cast Iron	DACE booklet	Flow & head	950, 25	m3/h, m	25.50
P-401C	Centrifugal pump	Cooling water circulation pump	Cast Iron	DACE booklet	Flow & head	950, 25	m3/h, m	25.50
P-401D	Centrifugal pump	Cooling water circulation pump	Cast Iron	DACE booklet	Flow & head	950, 25	m3/h, m	25.50
PM-101A	Pump motor	DCC circulation pump		DACE booklet	Inst. Power	45	kW	9.60
PM-101B	Pump motor	DCC circulation pump		DACE booklet	Inst. Power	45	kW	9.60
PM-101S	Pump motor	DCC circulation pump		DACE booklet	Inst. Power	45	kW	9.60
PM-102A	Pump motor	Rich amine pump		DACE booklet	Inst. Power	30	kW	4.80
PM-102B	Pump motor	Rich amine pump		DACE booklet	Inst. Power	30	kW	4.80
PM-102S	Pump motor	Rich amine pump		DACE booklet	Inst. Power	30	kW	4.80
PM-103A	Pump motor	Lean amine pump		DACE booklet	Inst. Power	40	kW	5.10
PM-103B	Pump motor	Lean amine pump		DACE booklet	Inst. Power	40	kW	5.10
PM-103S	Pump motor	Lean amine pump		DACE booklet	Inst. Power	40	kW	5.10
PM-104A	Pump motor	Wash water pump		DACE booklet	Inst. Power	45	kW	4.80
PM-104B	Pump motor	Wash water pump		DACE booklet	Inst. Power	45	kW	4.80
PM-104S	Pump motor	Wash water pump		DACE booklet	Inst. Power	45	kW	4.80
PM-105A	Pump motor	Stripper reflux pump		DACE booklet	Inst. Power	1	kW	0.31
PM-105S	Pump motor	Stripper reflux pump		DACE booklet	Inst. Power	1	kW	0.31
PM-120/121A	Pump motor	Steam condensate pump		DACE booklet	Inst. Power	6	kW	1.00
PM-120/121S	Pump motor	Steam condensate pump		DACE booklet	Inst. Power	6	kW	1.00
PM-401A	Pump motor	Cooling water circulation pump		DACE booklet	Inst. Power	130	kW	31.00
PM-401B	Pump motor	Cooling water circulation pump		DACE booklet	Inst. Power	130	kW	31.00
PM-401C	Pump motor	Cooling water circulation pump		DACE booklet	Inst. Power	130	kW	31.00
PM-401D	Pump motor	Cooling water circulation pump		DACE booklet	Inst. Power	130	kW	31.00
X-101	Package unit	Natural gas fired boiler system		Vendor quote				243.96
X-102	Package unit	Amine reclaimer unit	SS316	In-house data				155.00
X-103	Package unit	Amime solvent supply system	SS304	In-house data				10.00

4.13 Plot space assessment

Land available for development at Irving Oil Whitegate refinery has been assessed to identify the most suitable location for the carbon capture unit and the flue heated steam boilers. Details of the chosen plot spaces can be seen in aerial views of the refinery, see Appendix 1. The required net area, defined as the area that will be occupied by equipment including skid but excluding piping external from skids, auxiliary equipment walkways and driveways for maintenance can be found in table 4.13.1.

Tag. No.	Item	Service	Diameter mm	height mm	Width mm	Length, mm	net occupied area m2
E-101	S&T HX	Flue gas boiler including drum			930	3050	2,8
E-102	S&T HX	Flue gas boiler including drum			1330	2750	3,7
E-103	S&T HX	Flue gas boiler including drum			1580	3200	5,1
E-104	S&T HX	Flue gas boiler including drum			1000	3350	3,4
E-105	S&T HX	Flue gas boiler including drum			1380	3200	4,4
E-106A	S&T HX	Flue gas boiler including drum			1730	2700	4,7
E-106B	S&T HX	Flue gas boiler including drum			1730	2700	4,7
E-107	S&T HX	Flue gas boiler including drum			1830	3150	5,8
E-108	S&T HX	Flue gas boiler including drum			850	3600	3,1
E-109	S&T HX	Flue gas boiler including drum			600	2550	1,5
E-110A	S&T HX	Flue gas boiler including drum			700	1350	0,9
E-110B	S&T HX	Flue gas boiler including drum			700	1350	0,9
Net area flue gas treatment							**40,9**
A-101	Column vessel	DCC / Flue gas scrubber	5800				26,4
A-102	Column vessel	Absorber	6050				28,7
A-103	Column vessel	Stripper	3150				7,8
F-101A	Vessel	Amine activated Carbon /particle filter	2000	3500			3,1
F-101B	Vessel	Amine activated Carbon /particle filter	2000	3500			3,1
V-112	Drum	Stripper reflux drum	2000	3000			3,1
V-121	Drum	Condensate feed / flash tank	1700	4250			2,3
E-116A	S&T HX	Stripper reboiler			2060	5850	12,1
E-116B	S&T HX	Stripper reboiler			2060	5850	12,1
C-101A	Fan	Flue gas boiler Blower			3500	5000	17,5
C-101B	Fan	Flue gas boiler Blower			3500	5000	17,5
C-101C	Fan	Flue gas boiler Blower			3500	5000	17,5
E-111	P&F HX	DCC / FGS water cooler			2000	3000	6,0
E-112	P&F HX	Amine cooler			2000	2500	5,0
E-113	P&F HX	Combined amine cooler / heater			2000	4000	8,0
E-114	P&F HX	Absorber top cooler			2000	2500	5,0
E-115	P&F HX	Stripper condenser / Gas cooler			2000	4000	8,0
E-401	Dry cooler	Cooling water					1090
Net area Carbon capture plant							**1273,2**

Table 4.13.1 Net plot space occupied by equipment.

The available area is substantially larger than the required net area, 2500m2 vs 41 m2 for the plot space identified for flue gas treatment see figure 10.1.2, and 9500m2 vs 1273m2 for the plot space identified for the capture plant and dry coolers see figure 10.1.3. Based on these figures it can be concluded that there is sufficient plot space available for the gross area needed for the flue gas treatment and for the capture plant. The gross area will include the additional area needed for pipework eternal from skids, walkways and spacing guidelines that must be taken into account during detailed design of the project.

5 Operational costs (OPEX)

5.1 Introduction

Operational costs for the CO_2 capture plant can be divided into fixed and variable operating costs. Fixed production costs are costs that are incurred regardless of the plant operation rate or output. If the plant cuts back its production, these costs are not reduced.

The following costs are considered as fixed operating costs for the CO_2 capture plant:

- Labor costs
  - Plant operators
  - Plant engineers / supervisors
  - General plant overhead salaries (R&D, lab., amin., finance, etc.
- Maintenance costs
- Property taxes and insurances

The following costs are considered as variable operating costs in the CO_2 capture plant:

1. Utility consumptions
   - Electrical power
     - Pump motors
     - Flue gas booster motor
     - Dry-cooler fans
     - Amine reclaiming
     - Lighting, miscellaneous consumer
   - Natural gas
     - Fired boiler
   - Steam
     - Stripper reboiler
   - Demin water
     - Water balance amine system
   - Waste handling
     - Amine reclaimer waste is assumed to be treated as hazardous chemical waste. This needs to be investigated further as mentioned. in 3.8
2. Consumables
   - Amine solvent (to cover evaporation and degradation losses)
   - Caustic soda (for amine solvent reclaiming)
   - Activated carbon (for amine cleaning)

5.2 Utility and consumables prices

Figure 5.2.1. shows the leading European benchmark price development of natural gas over the last 12 years. It can be seen clearly that determining forward natural gas prices is extremely difficult. The impact of the Ukrainian war can be clearly as a huge spike in the prices. From current price level the price could drop further to pre-2020 levels. Therefore, a high and low-price scenario will be considered to see the effect on the CO_2 capture costs.

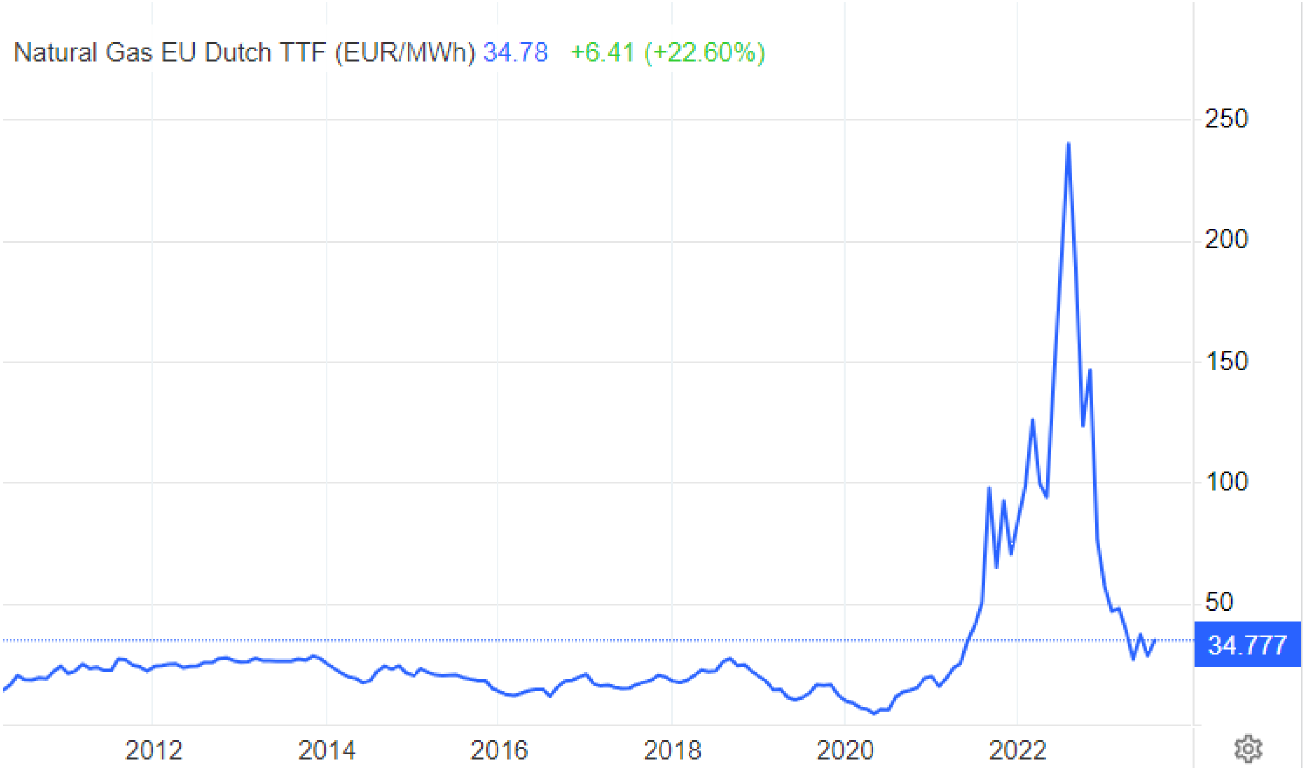


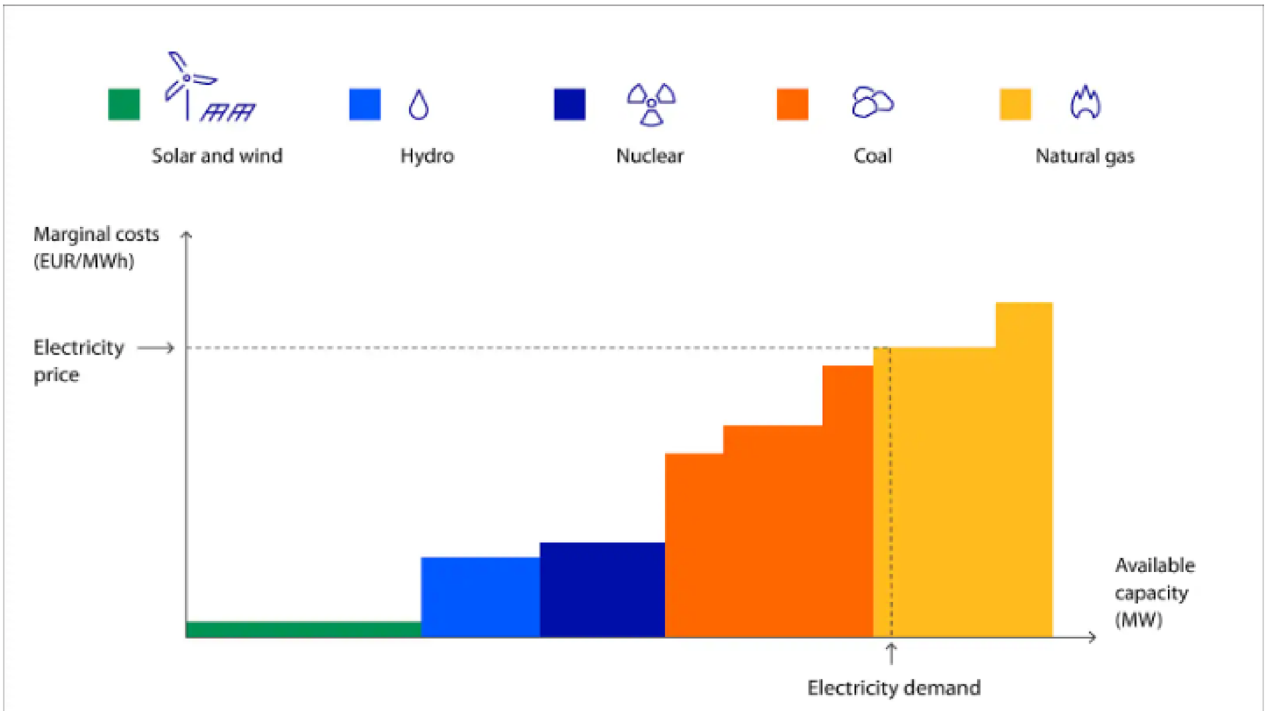
Figure 5.2.1: European Natural gas futures from 2011-2023, indicated price is current.

In many European countries, the prices of both power and natural gas are related, most of the time. However, electricity prices are not pegged to natural gas prices (RaboResearch,2022).

There are multiple wholesale electricity markets and therefore also multiple electricity prices.

Looking at the spot market, the match between supply and demand based on the marginal costs of the most expensive power plant in operation is what determines the electricity prices. This mechanism is known as a merit order (see Figure 5.2.2). Solar and wind farms can produce electricity at very low marginal costs, as they neither require fuel to produce electricity, nor carbon emissions allowances. At the other end of the spectrum, coal and natural gas-fired power plants must pay for fuel and buy carbon allowances. The exact position of these plants in the merit order always depends on the current prices of coal, natural gas, and carbon allowances, and on the efficiency of the plants e.g., natural gas fired Combined Cycle Power Plant (CCPP).

At present in Europe, the most expensive way to produce electricity is from natural gas. This means that it is now the natural gas-fired power plants that set electricity prices on the spot markets when the demand for electricity is high enough. This situation is currently common in many European markets. Therefore, there is a certain degree of correlation between electricity prices and natural gas prices in markets with a high share of gas-fired power plants in their electricity generation mix. However, the prices for these two commodities are not formally pegged. There are various instances where other types of power generators determine electricity prices. For example, even countries that still have a relatively low share of renewable power generation sources, such as the Netherlands, already benefit from very low or even negative electricity prices at times when demand is low and solar and wind farms can produce a lot of electricity. Similarly, in the northern parts of Norway, for example, hydropower plants are setting electricity spot prices most of the time. Another example comes from Poland, where coal-fired power plants often determine electricity prices.



Note: This figure presents a generic merit order curve. Depending on the installed electricity generation capacity, each power market has a different merit order curve. Furthermore, within the same market, the merit order curve can change depending on what part of the installed capacity is available to generate electricity. Source: RaboResearch 2022

Figure 5.2.2: Ranking of different sources of power production (merit order)

For the Irish market it is considered that for the near future the power price is to a certain extend correlated to the wholesale natural gas price.

The power plant near the Irving Oil Whitegate refinery produces electricity by a natural gas fired Combined Cycle (CCGT) Power Plant.

The forward power price from the CCGT can be calculated according to the following equation:

Forwarded power price = (whole sales gas price in €/MWh + carbon price in €/MWh)/power plant efficiency + spark spread. The spark spread is the difference between the wholesale market price of electricity and its cost of production using natural gas.

A spark spread of € 8/MWh is assumed by Pentair for the calculation of the whole sale power price for the Irish electricity generation market.

The CO_2 emission from natural gas firing = 0.2 MT/MWh thermal.

The current carbon emission price = € 85/MT

Figure 5.2.3 shows the development in the CO_2 emission prices over the last 15 years.

CO_2 permit prices are however expected to rise in the future.

The efficiency of the power plant is dependent on the load but is assumed to be 53%.

Now for a whole-sale natural gas price of €40/MWh the whole power price from the power plant would be:

(40 + 0.2*85)/0.53 + 8 = 115.5 €/MWh.

Figure 5.2.3. EU CO_2 permits since 2005.

Import steam from their power plant should be considered prized equal in €/MWh thermal to natural gas including carbon tax for this demonstration project study since it will likely be produced by additional duct burning of natural gas in the power plant.

Sensitivities on the natural gas /power and carbon tax prices will be discussed in Chapter 7.

Table 5.2.1. and 5.2.2. summarizes the respective utility and consumables prices considered as the base case for calculating the variable OPEX costs.

Utility	Price	Cost unit
Electricity	115.5	€/MWh
Natural gas without carbon tax	40	€/MWh therm.
Natural gas including carbon tax	57	€/MWh therm.
Steam	57	€/MWh
Demin water	1.19	€/ton

Table 5.2.1.: Utility prices base case

Consumable	Price	Cost unit
MEA solvent	3.4	€/kg
HS3 solvent	51	€/kg
Caustic soda	0.5	€/kg
Activated carbon	4.2	€/kg

Table 5.2.2.: Consumable prices base case

A non-carbon taxed natural gas price is considered for the fired boiler cases since the CO_2 from the flue gas will be captured for the most part. This is not the case for the import steam cases for the MEA and HS3 solvent where steam is imported from the nearby power plant where the CO_2 from the steam production is not captured.

It has been agreed with SINTEF that the cost of the HS3 solvent will be assumed as being 15 times higher than the cost of MEA in the economic evaluations. A sensitivity on the HS3 price is discussed in Chapter 7.

5.3 Fixed OPEX costs

Three (3) process operators and two (2) engineers/supervisors are considered annually for the CO_2 capture plant. The yearly salary for the process operator is assumed to be €55,000 and for the engineer/supervisor €75,000 per year.

Plant overhead costs are assumed to be 50% of the total direct labour cost.

Plant yearly maintenance cost is assumed to be 3% of the total plant cost (TPC) as discussed in chapter 6. Plant insurance and property tax costs are assumed to be 2% of TPC.

5.4 Utility and consumables consumptions

Utility and consumables consumptions for the considered scenarios are listed in table 5.4.1.

The utility and consumables consumptions for MEA and HS3 Case A are actually calculated in detail while for the B cases, a capacity factor is applied i.e. 0.9 for MEA Case B and 0.95 for HS3 case B.

The initial filling of MEA solvent for MEA Case A is estimated at 144 MT.

The initial filling of HS3 solvent for HS3 Case A is estimated at 138 MT.

The estimated solvent filling is based on the calculated estimated solvent inventories in the Absorber and Stripper column sump, amine packing sections, activated carbon filter, heat exchangers and amine circulation piping system.

Utility consumptions CO2 capture plant						
		MEA Case A	**MEA Case B**	**HS3 Case A**	**HS3 Case B**	
Power consumer	**Tag. No.**	**Value**	**Value**	**Value**	**Value**	**Unit**
Flue gas blower A	C-101A	300	268.6	300	286.7	kWh/h
Flue gas blower B	C-101B	300	268.6	300	286.7	kWh/h
Flue gas blower C	C-101C	300	268.6	300	286.7	kWh/h
Flue gas Scrubber circ. pump	P-101A	36.8	32.9	36.8	35.2	kWh/h
Flue gas Scrubber circ. pump	P-101B	36.8	32.9	36.8	35.2	kWh/h
Rich amine pump A	P-102A	26.3	23.5	21	20.1	kWh/h
Rich amine pump B	P-102B	26.3	23.5	21	20.1	kWh/h
Lean amine pump A	P-103A	31.6	28.3	24.2	23.1	kWh/h
Lean amine pump B	P-103B	31.6	28.3	24.2	23.1	kWh/h
Wash water circ. Pump A	P-104A	36.8	32.9	21	20.1	kWh/h
Wash water circ. Pump B	P-104B	36.8	32.9	21	20.1	kWh/h
Stripper reflux pump	P-105	0.87	0.8	0.63	0.6	kWh/h
LP steam condensate feed pump	P-120	5.1	5.1	3.7	3.7	kWh/h
Cooling water circ. pump A	P-401A	110	99.0	87	83.1	kWh/h
Cooling water circ. pump B	P-401B	110	99.0	87	83.1	kWh/h
Cooling water circ. pump C	P-401C	110	99.0	87	83.1	kWh/h
Reclaimer unit (heater + circ. Pump + heat tracing)	X-102	400	360.0	200	191.1	kWh/h
CW circulation dry-cooler	E-401	2070	1863.0	1882	1798.4	kWh/h
Miscellaneous consumers		15	15.0	15	14.3	kWh/h
Total		**3983.97**	**3582.06**	**3468.33**	**3314.37**	kWh/h
Natural gas consumer	**Tag. No.**	**Value**	**Value**	**Value**	**Value**	**Unit**
Natural gas fired steam boiler (LHV = 46790 kJ/kg, MW = 17.71)	X-101	1570	N.A.	712	N.A.	Nm3/h
Natural gas fired steam boiler (LHV = 46790 kJ/kg, MW = 17.71)	X-101	1241	N.A.	563	N.A.	kg/h
Natural gas fired steam boiler (LHV = 46790 kJ/kg, MW = 17.71)	X-101	16126	N.A.	7313	N.A.	kWh/h
LP steam import consumer	**Tag. No.**	**Value**	**Value**	**Value**	**Value**	**Unit**
Stripper reboiler	E-116	N.A.	18974	N.A.	8512	kg/h
Stripper reboiler	E-116	N.A,	11440	N.A,	5140	kWh/h
Demin water consumers		**Value**	**Value**	**Value**	**Value**	**Unit**
Balance water + make-up reclaimer		3500	3500	3000	3000	kg/h
Amine solvent consumption		**Value**	**Value**	**Value**	**Value**	
Amine losses due to evaporation and degradation losses		45	40.3	15.6	14.9	kg/h
Initial amine solvent filling		144,000	129,600	138,000	123,120	kg
Activated carbon consumers		**Value**	**Value**	**Value**	**Value**	
Amine solvent cleaning		1.5	1.3	1.1	1.1	kg/h
NaOH consumers		**Value**	**Value**	**Value**	**Value**	
Amine reclaiming process		36	32.2	12.5	11.9	kg/h

Table 5.4.1. Utility and consumables consumptions

6 Total Plant Cost (TPC) Estimation

6.1 Introduction Capital Cost Investment

Figure 6.1.1 gives an overview of the main elements of total capital investment or cost (TCI)
The focus in this study is on equipment installed cost. The capital investment expenditure (CAPEX) in this study is limited to the total plant cost (TPC), comprising the sum of all equipment installed costs.

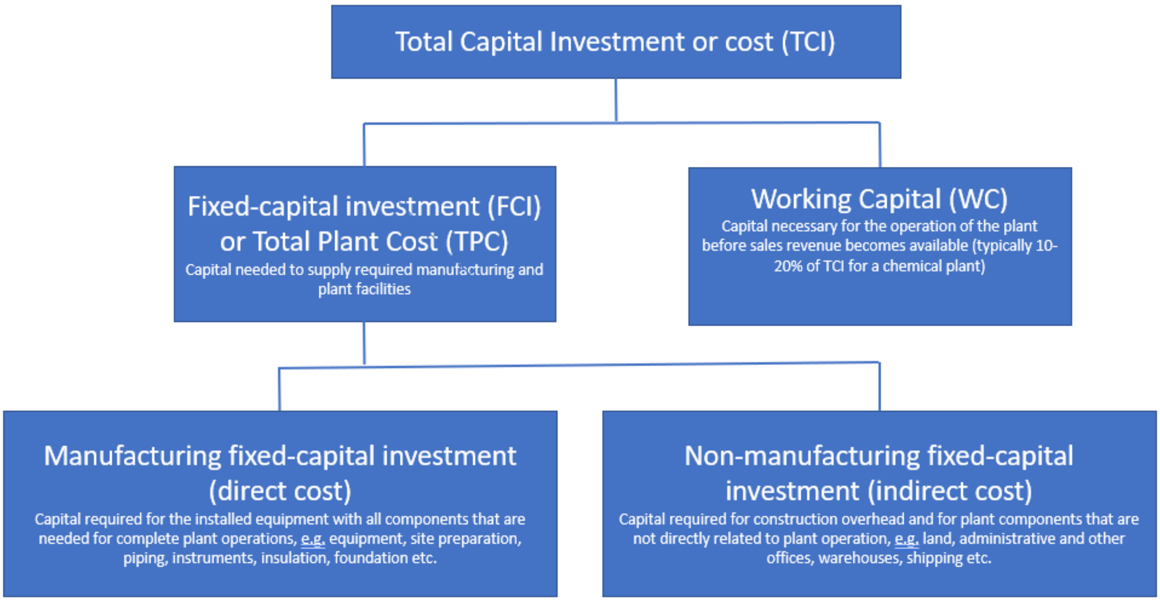


Figure 6.1.1. Elements of total capital investment (Eldrup,2021)

6.2 The EDF factorial method for Capital Cost Estimation

The delivered equipment costs are used as the basis for the calculation of the Total Plant Cost (TPC).
A so-called factorial method will be used to estimate the Total Plant Installed Cost (TPC) from the delivered equipment costs.

Figure 6.2.1 gives an overview of the elements constituting the process plant installation factor to derive the TPC.

Several categories of factorial methods are reported in literature of which the Lang and Hand factor method are well-known for an early-stage total plant cost estimation. Lang proposed a uniform installation factor to be applied on the sum of the total delivered cost of all major equipment items. For a fluid type of plant an overall installation factor of 4.74 is suggested.

Updates has been proposed for the Lang factor, ranging from 4.8 to 6.2 for fluid type of process plants. This method should only be applied in the very early stages of a project.

Hand (1958) suggested that more accurate results are obtained by using different installation factors for different type of equipment.

More detailed factorial estimates are outlined in A.M. Gerrard's guide to capital cost estimating. (Gerrard, 2000)

In each plant it is reasonable that the installation factors of less expensive equipment will be high, while very expensive equipment like compressors will have a lower installation factor.

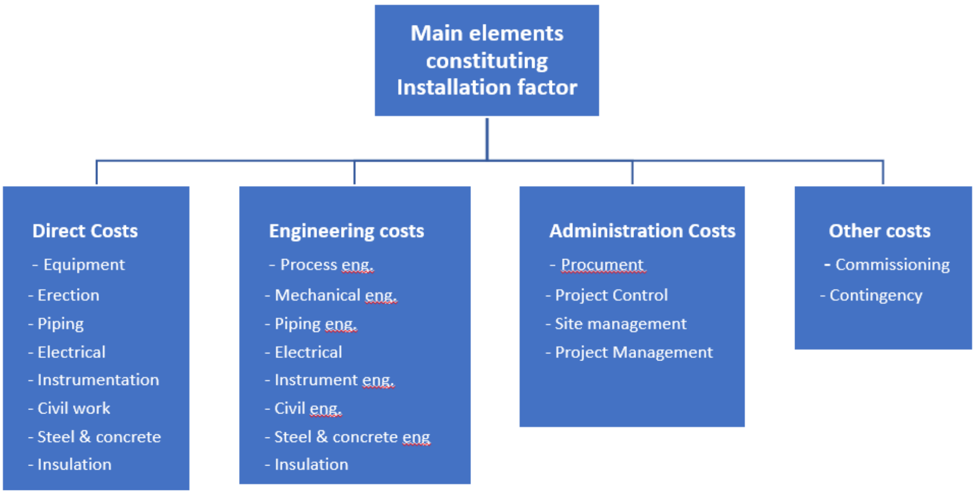


Figure 6.2.1: Main elements constituting Installation factor

Based on this principle, a more advanced factorial cost estimation technique has been presented in and published in 2021 as an open access article by the department Process, Energy and Environmental Technology from the University of South-Eastern Norway (NTNU) in cooperation with SINTEF Industry titled: 'Capital cost estimation of CO_2 capture plant using Enhanced Detailed Factor (EDF) method: Installation factors and plant construction characteristic factors'. (S.A. Aromada et al., 2021)
The most important aspect of the EDF method is the application of installation factors and subfactors to be applied on individual equipment costs depending on the delivered cost of each individual equipment item. Another vital aspect of the EDF method, is the effect each plant's construction characteristic or nature will have on the capital cost. These new important factors which will affect the capital cost estimates are given in Table 6.2.1, and they are termed plant construction characteristic factors (PCCF).

The PCCF was developed by Nils Eldrup (S.A. Aromada et al., 2021) based on industry experience and cost estimation in the pre-engineering phase, as well as experiences from construction. It was originally set up as a theory based on Gerrard (Gerrard, 2000).

Gerrard (Gerrard, 2000) had this as an adjustment on each equipment, but that was thought to be too elaborate. Thus, the list was developed to cover the "factory description", and eventually, they have been tested on real plants and adjusted over a period of 25 years.

EDF method's plant construction characteristic factors (PCCF).

Plant construction characteristics factors (PCCF)			
Instrument		**Insulation**	
Local instruments	0.36	No insulation	0.05
One control loop per main equipment	0.88	Heat insulation of utilities pipes	0.52
Two control loops per main equipment	0.94	Normal heat insulation	1.00
Tree control loops per main equipment	1.00	More than normal heat insulation	1.13
Electrical		Cold insulation of vessels and pipes	1.42
No electricity	0.09	**Ground preparation**	
Light	0.23	No ground preparation works	0.09
Light and electric power to building	0.82	Normal ground preparation without piling	1.00
Electric power from existing power supply	1.00	Normal ground preparation with piling	1.30
Electric power from new power supply	1.45	More than normal ground preparation without piling	2.16
Piping		More than normal ground preparation with piling	2.82
No piping	0.09	**Civil and buildings**	
Channels	0.27	No buildings	0.09
Thin pipes and pipes for utilities systems	0.67	Open on ground	0.28
Normal pipes and pipes for utilities	1.00	Open in a structure	0.78
Complex pipes and pipes for utilities	1.12	Closed structure	1.00
Big bore pipe and pipe for utilities	1.12	Insulated closed structure	1.60
Big bore and complex pipes and pipes for utilities	1.29	More than normal ground preparation with piling	2.82

Table 6.2.1 : EDF method's plant construction characteristic factors (PCCF).

The PCCFs are applied on (i.e., multiply by) their corresponding subfactors both in the direct cost (material) and the engineering subfactors. For example, if there is no need for ground preparation, then, the subfactor "ground work" in the direct cost as well as the "engineering ground" subfactor in Table 6.2.1 must be multiplied by the corresponding PCCF of 0.09 in Table 6.2.2 under "ground preparation".

This ensures a more realistic capital cost estimation. In the EDF method, different total equipment installation factors and subfactors are applied to different equipment based on their various costs (Free On Board-FOB). The method has installation factors and subfactors prepared assuming in carbon steel (CS) and are more detailed. A very costly piece of equipment has a low installation factor, and a less expensive one has a higher installation factor. Where an expensive material such as stainless steel is used to manufacture any of the main plant equipment, the appropriate correction due to the material is implemented, and the mode of construction (welded or machined) is also considered. The method treats every piece of equipment as a separate project. It shows the individual contribution of each piece of equipment to the capital cost, thereby highlighting the major cost drivers for possible optimisation.

The EDF method makes the estimates more transparent since one can see and adjust the individual contributions to the total installed cost of a piece of equipment.

The capital investment or expenses (CAPEX) applying the EDF method is limited to the total plant cost (TPC). This comprises the sum of all equipment installed costs.

If deemed necessary, adjustments can be made in the applied installation factors and sub-factors like the PCCF’s.

EDF method's Installation Factors Sheet for fluid handling equipment installation-prepared by Nils Henrik Eldrup, 2020 (USN and SINTEF Tel-Tek).

EDF method installation factors for fluid handling equipment											
Equipment costs (CS) in 1000 €:	0 - 10	10 - 20	20 - 40	40 - 80	80 - 160	160 - 320	320 - 640	640 - 1280	1280 - 2560	2560 - 5120	5120 - 10240
Equipment cost	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Erection cost	0.49	0.33	0.26	0.20	0.16	0.12	0.09	0.07	0.06	0.04	0.03
Piping incl. Erection	2.24	1.54	1.22	0.96	0.76	0.60	0.48	0.38	0.30	0.23	0.19
Electro (equip. & erection)	0.76	0.59	0.51	0.44	0.38	0.32	0.28	0.24	0.20	0.18	0.15
Instrument (equip. & erection)	1.50	1.03	0.81	0.64	0.51	0.40	0.32	0.25	0.20	0.16	0.12
Ground work	0.27	0.21	0.18	0.15	0.13	0.11	0.09	0.08	0.07	0.06	0.05
Steel & concrete	0.85	0.66	0.55	0.47	0.40	0.34	0.29	0.24	0.20	0.17	0.15
Insulation	0.28	0.18	0.14	0.11	0.08	0.06	0.05	0.04	0.03	0.02	0.02
Direct costs	7.38	5.54	4.67	3.97	3.41	2.96	2.59	2.30	2.06	1.86	1.71
Engineering process	0.44	0.27	0.22	0.18	0.15	0.12	0.10	0.09	0.07	0.06	0.05
Engineering mechanical	0.32	0.16	0.11	0.08	0.06	0.05	0.03	0.03	0.02	0.02	0.01
Engineering piping	0.67	0.46	0.37	0.29	0.23	0.18	0.14	0.11	0.09	0.07	0.06
Engineering el.	0.33	0.20	0.15	0.12	0.10	0.08	0.07	0.06	0.05	0.04	0.04
Engineering instr.	0.59	0.36	0.27	0.20	0.16	0.12	0.10	0.08	0.06	0.05	0.04
Engineering ground	0.10	0.05	0.04	0.03	0.02	0.02	0.01	0.01	0.01	0.01	0.01
Engineering steel & concrete	0.19	0.12	0.09	0.08	0.06	0.05	0.04	0.04	0.03	0.03	0.02
Engineering insulation	0.07	0.04	0.03	0.02	0.01	0.01	0.01	0.01	0.00	0.00	0.00
Engineering	2.70	1.66	1.27	0.99	0.79	0.64	0.51	0.42	0.34	0.28	0.23
Procurement	1.15	0.38	0.48	0.48	0.24	0.12	0.06	0.03	0.01	0.01	0.00
Project control	0.14	0.08	0.06	0.05	0.04	0.03	0.03	0.02	0.02	0.01	0.01
Site management	0.37	0.28	0.23	0.20	0.17	0.15	0.13	0.11	0.10	0.09	0.09
Project management	0.45	0.30	0.26	0.22	0.18	0.15	0.13	0.11	0.10	0.09	0.08
Administration	2.10	1.04	1.03	0.94	0.63	0.45	0.34	0.27	0.23	0.20	0.18
Commissioning	0.31	0.19	0.14	0.11	0.08	0.06	0.05	0.04	0.03	0.02	0.02
Identified costs	12.48	8.43	7.11	6.02	4.91	4.10	3.49	3.02	2.66	2.37	2.13
Contingency	2.50	1.69	1.42	1.20	0.98	0.82	0.70	0.60	0.53	0.47	0.43
Installation factor 2020	14.98	10.12	8.54	7.22	5.89	4.92	4.19	3.63	3.19	2.84	2.56
Adjustment for material	Equipment & piping factors multiplies with										
Carbon steel (CS)	1.00										
Stainless steel SS316 (welded)	1.75										
Stainless steel SS316, rotating equipment (Machined)	1.30										
Glass-reinforced plastic (GRP)	1.40										
Exotic material (welded)	2.50										
Exotic material, rotating equipment (machined)	1.75										

Table 6.2.2: EDF method's Installation Factors Sheet for fluid handling equipment installation-prepared by Nils Henrik Eldrup, 2020 (USN and SINTEF Tel-Tek). Default plant location is Rotterdam, The Netherlands. Cost year is 2020.

AACE International Recommended Practice No. 18R-97 recognizes several classes of cost estimates for the process industry as a function of the maturity level of the project definition deliverables as indicated in below table 6.2.3.

COST ESTIMATE CLASSIFICATION MATRIX FOR THE PROCESS INDUSTRIES

	Primary Characteristic	*Secondary Characteristic*		
ESTIMATE CLASS	**MATURITY LEVEL OF PROJECT DEFINITION DELIVERABLES** Expressed as % of complete definition	**END USAGE** Typical purpose of estimate	**METHODOLOGY** Typical estimating method	**EXPECTED ACCURACY RANGE** Typical variation in low and high ranges [a]
Class 5	0% to 2%	Concept screening	Capacity factored, parametric models, judgment, or analogy	L: -20% to -50% H: +30% to +100%
Class 4	1% to 15%	Study or feasibility	Equipment factored or parametric models	L: -15% to -30% H: +20% to +50%
Class 3	10% to 40%	Budget authorization or control	Semi-detailed unit costs with assembly level line items	L: -10% to -20% H: +10% to +30%
Class 2	30% to 75%	Control or bid/tender	Detailed unit cost with forced detailed take-off	L: -5% to -15% H: +5% to +20%
Class 1	65% to 100%	Check estimate or bid/tender	Detailed unit cost with detailed take-off	L: -3% to -10% H: +3% to +15%

Notes: [a] The state of process technology, availability of applicable reference cost data, and many other risks affect the range markedly. The +/- value represents typical percentage variation of actual costs from the cost estimate after application of contingency (typically at a 50% level of confidence) for given scope.

Table 6.2.3 – Cost Estimate Classification Matrix for the Process Industries

Another way to look at the variability associated with estimate accuracy ranges is shown in Figure 6.2.1. Depending upon the technical complexity of the project, the availability of appropriate cost reference information, the degree of project definition, and the inclusion of appropriate contingency determination, a typical Class 5 estimate for a process industry project may have an accuracy range as broad as -50% to +100%, or as narrow as -20% to +30%.

Figure 6.2.1 also illustrates that the estimating accuracy ranges overlap the estimate classes. There are cases where a Class 5 estimate for a particular project may be as accurate as a Class 3 estimate for a different project. For example, similar accuracy ranges may occur for the Class 5 estimate of one project that is based on a repeat project with good cost history and data and the Class 3 estimate for another project involving new technology. It is for this reason that Table 1 provides ranges of accuracy range values. The accuracy range is determined through risk analysis of the specific project.

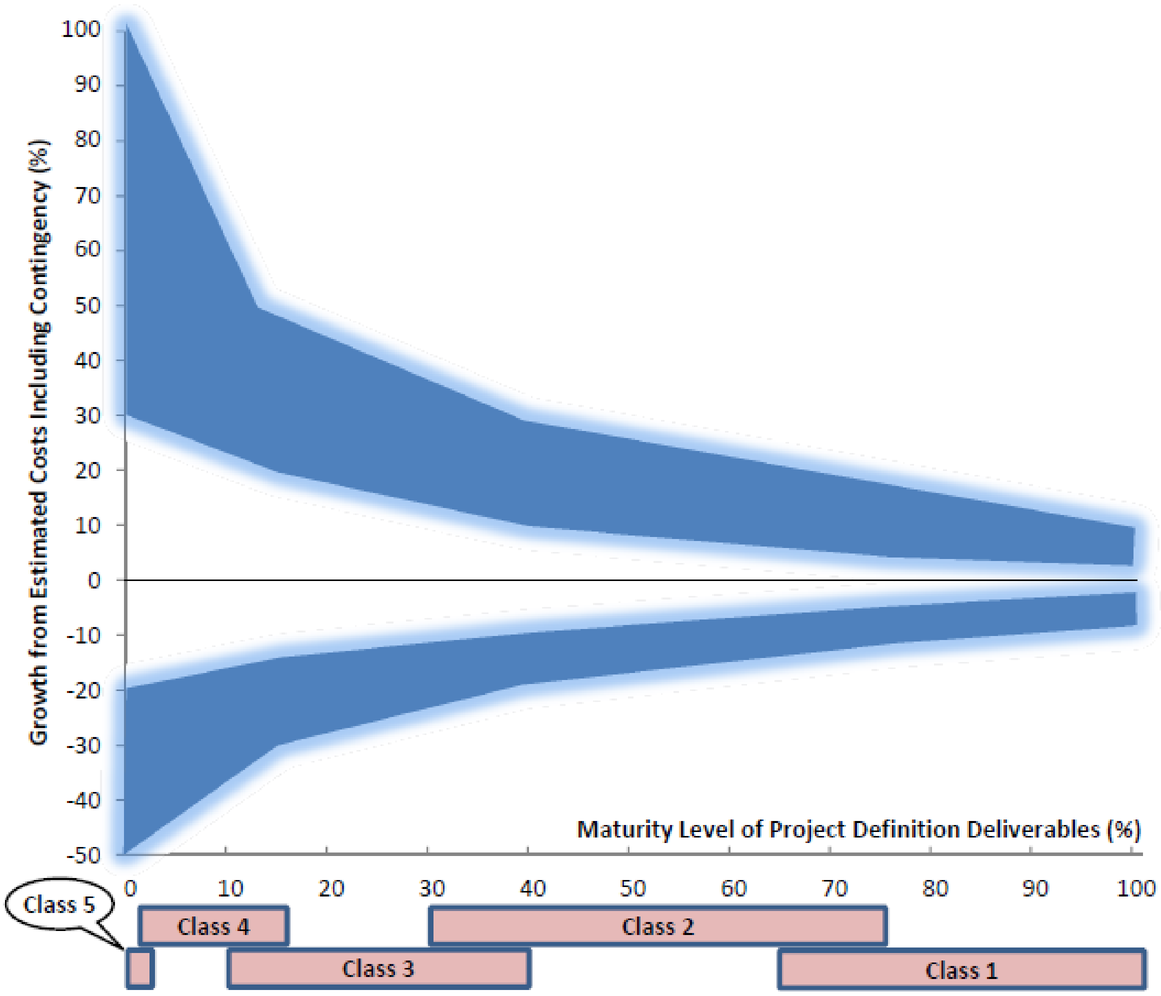


Figure 6.2.1. – Example of the variability in accuracy ranges for a process industry cost estimate

Based upon the current maturity level of the project definition for the four (4) considered scenarios it is anticipated that a Class 3 cost estimate is feasible when applying the EDF method for total plant cost. It is confirmed by the developer of the EDF method that an accuracy of +/- 25% can be reached by applying the EDF method if the TPC is within 25% accuracy.

Applying a uniform installation factor, such as the Lang factor will result in Class 4 estimate at best.

The EDF method comprises the following steps to estimate the TPC (Ali et al., 2019):

1. Prepare a flowsheet of the plant and list the major plant equipment.
2. Compute the material and energy balance of the process either through process simulations or by hand calculation.
3. Perform equipment dimensioning/sizing based on the material and energy balances.
4. Estimate the cost of each piece of equipment from a reliable source.
5. It is convenient to list the equipment in a spreadsheet with their purchase costs.
6. Convert the purchase cost of each piece of equipment in material other than carbon steel to its corresponding cost in carbon steel using the appropriate material factor in Table 6.2.4. This is because the installation factors are in CS.
7. Obtain the appropriate total installation factor in CS for each piece of equipment.
8. Correction of specific subfactors may be required based on the nature or characteristics of the construction works. For example, if more than the normal heat insulation is required due to very cold weather in the plant specific location, then, the insulation subfactor in both direct cost and engineering subfactors in Table 6.2.2 must be corrected by multiplication with the corresponding specific construction factor in Table 6.2.1.
9. Calculate the installation factors for all equipment in another material (SS304 or 316) accounting for the material and piping.
10. Estimate an equipment installed cost, multiply the cost of each piece of equipment in CS by the total installation factor in CS (standard installation factor). For the equipment in another material (SS304 or SS316), multiply the cost of each piece of equipment in CS by the total installation factor in the other material (SS304 or 316) as per below equations (2), (3) and (4), (5) and (6).
11. For any equipment that has more than one piece or unit, multiply it by the number of units to obtain the total installed cost for that equipment.
12. The total plant cost is the sum of all the equipment installed cost.

The installation factors are for equipment in carbon steel (CS), therefore, conversion of cost of equipment in other materials such as stainless steel to cost in CS is necessary. This is simply done as follows using an appropriate factor in Table 6.2.4.:

$$C_{Eq.,CS} = \frac{C_{other\ matl.}}{f_m} \qquad (1)$$

Where,

$C_{Eq.,CS}$ = cost of equipment in carbon steel

$C_{Eq.,\ other\ mat.}$ = cost of equipment in other material

f_M = material factor for converting cost in other materials to cost in CS

After converting the equipment cost in SS to CS, the appropriate total installation factors for the piece of equipment in CS can be obtained from Table 6.2.2. This can be represented as:

$F_{T,CS} = f_{direct} + f_{engineering} + f_{administration} + f_{commissioning} + f_{contingency}$ (2)

For equipment bought in other materials, the installation factors need to be converted from CS back to the original material. It is important to understand that it is only the equipment material and piping that will be affected. Therefore, the final EDF installation factor for any piece of equipment in other material can be estimated by subtracting the equipment factor (usually 1) and piping sub-factor in CS from $F_{T,CS}$, then add the equipment subfactor and piping sub-factor in the other material as shown in equation (3), and rearranged to (4):

$F_{T,other\ mat.} = F_{T,CS} - (f_{Eq.} + f_{pp,CS}) + f_M(f_{Eq.} + F_{pp,CS})$ (3)

$F_{T,other\ mat.} = F_{T,CS} + (f_m - 1).(f_{Eq.} + F_{pp,CS})$ (4)

The installed cost of each piece of equipment in CS, and in other materials and the TPC can then be estimated using equation (5), (6) and (7) respectively:

$C_{EIC,\ CS} = C_{Eq.,\ CS}.F_{T,\ CS}$ (5)

$C_{EIC,\ other\ mat.} = C_{Eq.,\ CS}.F_{T,\ other\ mat.}$ (6)

$TPC = \sum(All\ equipment\ installed\ costs)$ (7)

Material of construction	Material factor, f_M
Carbon steel	1.00
304 stainless steel (machined)	1.20
304 stainless steel (welded)	1.60
316 stainless steel (machined)	1.30
316 stainless steel (welded)	1.75

Table 6.2.4. Material factors used in the EDF method.

6.3 CEPCI Index

The equipment cost prices are 2023 price levels.

The installation factors in the described EDF method are determined based on year 2020 price levels. Equipment costs have therefore to be corrected to 2020 price levels. For this, the so-called Chemical Engineering Plant Cost Index (CEPCSI) is used. The indices from the year 2020 to 2023 are listed in Table 6.3.1.

Year	**CEPCI**
2023 Mar	799.5
2023 Feb	798,0
2023 Jan	802.6
2022 Dec	802.9
2022 Nov	814.6
2022 Oct	816.2
2022 Sep	821.3
2022 Aug	824.5
2022 Jul	829.8
2022 Jun	832.6
2022 May	831.1
2022 Apr	816.3
2022 Mar	803.6
2022 Feb	801.3
2022 Jan	797.6
2021 Dec	776.3
2021 Nov	773.1
2021 Oct	761.4
2021 Sep	754
2021 Aug	735.2
2021 Jul	720.2
2021 Jun	701.4
2021 May	686.7
2021 Apr	677.1
2022	816
2021	708.8
2020	596.2

Table 6.3.1. CEPCI 2020 to Mar 2023

6.4 Total Installed Plant Costs (TPC)

The EDF method costing calculation sheets with the estimations of the TPC for each of the four different CO_2 capture scenarios are shown in table 6.4.1 – 6.4.4

As mentioned in Chapter 4, the equipment costs for MEA and HS3 Case B are derived from the so-called ‘six-tenth factor’ principle as can be seen in table 6.4.2. and 6.4.4.

The estimated TPC’s are considered to have an accuracy of +/- 25%.
A sensitivity on the equipment cost accuracy for the CO_2 capture cost will be discussed in Chapter 7.

Costing sheet - MEA Case A			2023 price Cost per Unit, k€	CEPSI Apr-23	CEPSI 2020	2020 price Cost per Unit, k€	Mat'l factor	Cost in CS k€	Std. Inst. fact. (CS)	Piping factor	PCCF corr.	PCCF corr. Installation factor (CS)	Total act. Inst. factor	2020 Total Inst. Cost, k€	2023 Total Inst. Cost, k€
Equipment	Tag. No.	Material													
DCC column shell, nozzles & skirt	A-101	SS304 (welded)	1,100.0	803.2	596.2	816.47	1.60	687.50	3.28	0.44	-0.36	2.92	3.79	**2,604.2**	**3,508.5**
DCC column internals	A-101	SS304 (welded)	170.0	803.2	596.2	126.18	1.60	106.25	4.85	0.76	-1.05	3.80	4.85	**515.5**	**694.5**
Absorber column shell, nozzles & skirt	A-102	SS304 (welded)	1,475.0	803.2	596.2	1094.81	1.60	921.88	3.35	0.38	-0.29	3.05	3.88	**3,579.5**	**4,822.5**
Absorber column internals	A-102	SS304 (welded)	850.0	803.2	596.2	630.91	1.60	531.25	3.48	0.48	-0.72	2.77	3.65	**1,941.3**	**2,615.4**
Stripper column shell, nozzles & skirt	A-103	SS304 (welded)	900.0	803.2	596.2	668.02	1.60	562.50	3.86	0.48	-0.34	3.52	4.40	**2,477.1**	**3,337.4**
Stripper column internals	A-103	SS304 (welded)	240.0	803.2	596.2	178.14	1.60	150.00	4.85	0.76	-1.05	3.80	4.85	**727.7**	**980.4**
Fluegas blower	C-101A	SS304 (Machined)	75.3	803.2	596.2	55.89	1.20	62.75	6.94	0.96	-0.29	6.64	7.03	**441.3**	**594.5**
Fluegas blower	C-101B	SS304 (Machined)	75.3	803.2	596.2	55.89	1.20	62.75	6.94	0.96	-0.29	6.64	7.03	**441.3**	**594.5**
Fluegas blower	C-101C	SS304 (Machined)	75.3	803.2	596.2	55.89	1.20	62.75	6.94	0.96	-0.29	6.64	7.03	**441.3**	**594.5**
Flue gas boiler - steam/cond. Drum + internals	V-101	CS	31.9	803.2	596.2	23.68	1.00	31.90	8.02	1.41	-0.52	7.49	7.49	**239.1**	**322.1**
Flue gas boiler - steam/cond. Drum + internals	V-102	CS	33.9	803.2	596.2	25.16	1.00	33.90	8.02	1.41	-0.52	7.49	7.49	**254.0**	**342.3**
Flue gas boiler - steam/cond. Drum + internals	V-103	CS	42.0	803.2	596.2	31.17	1.00	42.00	6.78	1.11	-0.45	6.32	6.32	**265.6**	**357.9**
Flue gas boiler - steam/cond. Drum + internals	V-104	CS	32.3	803.2	596.2	23.97	1.00	32.30	8.02	1.41	-0.52	7.49	7.49	**242.1**	**326.1**
Flue gas boiler - steam/cond. Drum + internals	V-105	CS	36.8	803.2	596.2	27.31	1.00	36.80	8.02	1.41	-0.52	7.49	7.49	**275.8**	**371.5**
Flue gas boiler - steam/cond. Drum + internals	V-106A	CS	41.8	803.2	596.2	31.03	1.00	41.80	6.78	1.11	-0.45	6.32	6.32	**264.4**	**356.2**
Flue gas boiler - steam/cond. Drum + internals	V-106B	CS	41.8	803.2	596.2	31.03	1.00	41.80	6.78	1.11	-0.45	6.32	6.32	**264.4**	**356.2**
Flue gas boiler - steam/cond. Drum + internals	V-107	CS	39.3	803.2	596.2	29.17	1.00	39.30	8.02	1.41	-0.52	7.49	7.49	**294.5**	**396.8**
Flue gas boiler - steam/cond. Drum + internals	V-108	CS	30.8	803.2	596.2	22.86	1.00	30.80	8.02	1.41	-0.52	7.49	7.49	**230.8**	**311.0**
Flue gas boiler - steam/cond. Drum + internals	V-109	CS	28.2	803.2	596.2	20.93	1.00	28.20	8.02	1.41	-0.52	7.49	7.49	**211.3**	**284.7**
Flue gas boiler - steam/cond. Drum + internals	V-110A	CS	27.0	803.2	596.2	20.04	1.00	27.00	8.02	1.41	-0.52	7.49	7.49	**202.3**	**272.6**
Flue gas boiler - steam/cond. Drum + internals	V-110B	CS	27.0	803.2	596.2	20.04	1.00	27.00	8.02	1.41	-0.52	7.49	7.49	**202.3**	**272.6**
Amine act. Carbon filter + particle filter + fillings	F-101A	CS	142.0	803.2	596.2	105.40	1.00	142.00	5.00	0.76	-0.90	4.10	4.10	**582.3**	**784.5**
Amine act. Carbon filter + particle filter + fillings	F-101B	CS	142.0	803.2	596.2	105.40	1.00	142.00	5.00	0.76	-0.90	4.10	4.10	**582.3**	**784.5**
Stripper reflux drum	V-112	SS304 (welded)	52.8	803.2	596.2	39.19	1.60	33.00	7.83	1.22	-0.71	7.11	8.44	**278.7**	**375.4**
LP steam condensate collection drum	V-121	CS	36.0	803.2	596.2	26.72	1.00	36.00	7.83	1.22	-0.71	7.11	7.11	**256.0**	**345.0**
Flue gas boiler - heat exchanger	E-101	SS304 (welded)	70.7	803.2	596.2	52.48	1.60	44.19	6.78	1.11	-0.45	6.32	7.59	**335.4**	**451.9**
Flue gas boiler - heat exchanger	E-102	SS304 (welded)	102.6	803.2	596.2	76.15	1.60	64.13	6.78	1.11	-0.45	6.32	7.59	**486.8**	**655.8**
Flue gas boiler - heat exchanger	E-103	SS304 (welded)	159.2	803.2	596.2	118.17	1.60	99.50	5.51	0.88	-0.39	5.12	6.24	**621.2**	**836.9**
Flue gas boiler - heat exchanger	E-104	SS304 (welded)	73.8	803.2	596.2	54.78	1.60	46.13	6.78	1.11	-0.45	6.32	7.59	**350.1**	**471.7**
Flue gas boiler - heat exchanger	E-105	SS304 (welded)	116.2	803.2	596.2	86.25	1.60	72.63	6.78	1.11	-0.45	6.32	7.59	**551.3**	**742.7**
Flue gas boiler - heat exchanger	E-106A	SS304 (welded)	167.0	803.2	596.2	123.95	1.60	104.38	5.51	0.88	-0.39	5.12	6.24	**651.6**	**877.9**
Flue gas boiler - heat exchanger	E-106B	SS304 (welded)	167.0	803.2	596.2	123.95	1.60	104.38	5.51	0.88	-0.39	5.12	6.24	**651.6**	**877.9**
Flue gas boiler - heat exchanger	E-107	SS304 (welded)	176.5	803.2	596.2	131.01	1.60	110.31	5.51	0.88	-0.39	5.12	6.24	**688.7**	**927.8**
Flue gas boiler - heat exchanger	E-108	SS304 (welded)	62.6	803.2	596.2	46.46	1.60	39.13	8.02	1.41	-0.52	7.49	8.94	**349.8**	**471.3**
Flue gas boiler - heat exchanger	E-109	SS304 (welded)	36.9	803.2	596.2	27.39	1.60	23.06	8.02	1.41	-0.52	7.49	8.94	**206.2**	**277.8**
Flue gas boiler - heat exchanger	E-110A	SS304 (welded)	36.0	803.2	596.2	26.72	1.60	22.50	8.02	1.41	-0.52	7.49	8.94	**201.2**	**271.0**
Flue gas boiler - heat exchanger	E-110B	SS304 (welded)	36.0	803.2	596.2	26.72	1.60	22.50	8.02	1.41	-0.52	7.49	8.94	**201.2**	**271.0**
Stripper reboiler	E-116A	SS304 (welded)	534.1	803.2	596.2	396.43	1.60	333.81	3.83	0.48	-0.37	3.47	4.35	**1,453.2**	**1,957.9**
Stripper reboiler	E-116B	SS304 (welded)	534.1	803.2	596.2	396.43	1.60	333.81	3.83	0.48	-0.37	3.47	4.35	**1,453.2**	**1,957.9**
DCC water circulation cooler	E-111	SS316 (welded)	234.0	803.2	596.2	173.69	1.75	133.71	5.39	0.76	-0.51	4.88	6.20	**828.8**	**1,116.6**
Amine cooler	E-112	SS316 (welded)	47.3	803.2	596.2	35.11	1.75	27.03	7.83	1.22	-0.71	7.11	8.78	**237.2**	**319.6**
Combined amine cooler / heater	E-113	SS316 (welded)	381.2	803.2	596.2	282.94	1.75	217.83	4.49	0.60	-0.43	4.06	5.26	**1,145.8**	**1,543.7**
Absorber top cooler	E-114	SS316 (welded)	107.9	803.2	596.2	80.09	1.75	61.66	6.50	0.96	-0.73	5.78	7.25	**446.9**	**602.1**
Stripper condenser	E-115	SS316 (welded)	62.9	803.2	596.2	46.69	1.75	35.94	7.83	1.22	-0.71	7.11	8.78	**315.5**	**425.0**
DCC circulation pump + motor	P-101A	SS316 (Machined)	43.1	803.2	596.2	31.99	1.30	33.15	8.17	1.22	-0.37	7.81	8.47	**280.9**	**378.4**
DCC circulation pump + motor	P-101B	SS316 (Machined)	43.1	803.2	596.2	31.99	1.30	33.15	8.17	1.22	-0.37	7.81	8.47	**280.9**	**378.4**
DCC circulation pump + motor	P-101S	SS316 (Machined)	43.1	803.2	596.2	31.99	1.30	33.15	8.17	1.22	-0.37	7.81	8.47	**280.9**	**378.4**
Rich amine pump + motor	P-102A	SS316 (Machined)	30.3	803.2	596.2	22.49	1.30	23.31	8.33	1.22	-0.21	8.13	8.79	**205.0**	**276.2**
Rich amine pump + motor	P-102B	SS316 (Machined)	30.3	803.2	596.2	22.49	1.30	23.31	8.33	1.22	-0.21	8.13	8.79	**205.0**	**276.2**
Rich amine pump + motor	P-102S	SS316 (Machined)	30.3	803.2	596.2	22.49	1.30	23.31	8.33	1.22	-0.21	8.13	8.79	**205.0**	**276.2**
Lean amine pump + motor	P-103A	SS316 (Machined)	29.8	803.2	596.2	22.12	1.30	22.92	8.33	1.22	-0.21	8.13	8.79	**201.6**	**271.6**
Lean amine pump + motor	P-103B	SS316 (Machined)	29.8	803.2	596.2	22.12	1.30	22.92	8.33	1.22	-0.21	8.13	8.79	**201.6**	**271.6**
Lean amine pump + motor	P-103S	SS316 (Machined)	29.8	803.2	596.2	22.12	1.30	22.92	8.33	1.22	-0.21	8.13	8.79	**201.6**	**271.6**
Wash water circulation pump + motor	P-104A	SS316 (Machined)	37.6	803.2	596.2	27.91	1.30	28.92	8.17	1.22	-0.37	7.81	8.47	**245.0**	**330.1**
Wash water circulation pump + motor	P-104B	SS316 (Machined)	37.6	803.2	596.2	27.91	1.30	28.92	8.17	1.22	-0.37	7.81	8.47	**245.0**	**330.1**
Wash water circulation pump + motor	P-104S	SS316 (Machined)	37.6	803.2	596.2	27.91	1.30	28.92	8.17	1.22	-0.37	7.81	8.47	**245.0**	**330.1**
Stripper reflux pump + motor	P-105A	SS316 (Machined)	6.9	803.2	596.2	5.12	1.30	5.31	14.67	2.24	-0.35	14.31	15.28	**81.1**	**109.3**
Stripper reflux pump + motor	P-105S	SS316 (Machined)	6.9	803.2	596.2	5.12	1.30	5.31	14.67	2.24	-0.35	14.31	15.28	**81.1**	**109.3**
LP steam condensate pump + motor	P-121A	SS316 (Machined)	14.2	803.2	596.2	10.50	1.30	10.88	9.87	1.54	-0.26	9.61	10.37	**112.9**	**152.1**
LP steam condensate pump + motor	P-121S	SS316 (Machined)	14.2	803.2	596.2	10.50	1.30	10.88	9.87	1.54	-0.26	9.61	10.37	**112.9**	**152.1**
Cooling water circulation pump + motor	P-401A	CS	70.0	803.2	596.2	51.96	1.00	70.00	6.94	0.96	-0.29	6.64	6.64	**464.8**	**626.2**
Cooling water circulation pump + motor	P-401B	CS	70.0	803.2	596.2	51.96	1.00	70.00	6.94	0.96	-0.29	6.64	6.64	**464.8**	**626.2**
Cooling water circulation pump + motor	P-401C	CS	70.0	803.2	596.2	51.96	1.00	70.00	6.94	0.96	-0.29	6.64	6.64	**464.8**	**626.2**
Cooling water circulation pump + motor	P-401S	CS	70.0	803.2	596.2	51.96	1.00	70.00	6.94	0.96	-0.29	6.64	6.64	**464.8**	**626.2**
Cooling water dry-cooler + fan motors	E-401	CS	4,600.0	803.2	596.2	3414.33	1.00	4600.00	2.75	0.23	-0.08	2.68	2.68	**12,322.5**	**16,601.6**
Natural gas fired steam boiler unit	X-101	CS	382.6	803.2	596.2	283.98	1.00	382.60	3.80	0.48	-0.40	3.40	3.40	**1,302.1**	**1,754.2**
Amine reclaimer unit	X-102	SS316 (welded)	335.0	803.2	596.2	248.65	1.75	191.43	3.72	-0.11	-1.19	2.52	3.19	**610.2**	**822.2**
Amine solvent supply system	X-103	SS304 (welded)	20.0	803.2	596.2	14.84	1.60	12.50	9.57	1.54	-0.55	9.03	10.55	**131.9**	**177.7**
Total equipment cost (TEC) & Total plant cost (TPC), k€		**k€**	**14,934.6**										**4.37**	**48,402.0**	**65,210.3**

Table 6.4.1. Total Installed Plant (TPC) cost MEA Case A

EDF method - Costing sheet - MEA Case B			MEA Case A 2023 price Cost per Unit, k€	MEA Case B Cap. Factor	Cost Scale Exp.	MEA Case B 2023 price Cost per Unit, k€	CEPSI Apr-23	CEPSI 2020	2020 price Cost per Unit, k€	Mat'l factor	Cost in CS k€	Std. Inst. fact. (CS)	Piping factor	PCCF corr.	PCCF Corr. Inst. fact. (CS)	Total Act. Inst. factor	2020 Total Inst. Cost, k€	2023 Total Inst. Cost, k€
Equipment	Tag. No.	Material																
DCC column shell, nozzles & skirt	A-101	SS304 (welded)	1,100.0	0.90	0.75	1,016.42	803.2	596.2	754.43	1.60	635.26	3.79	0.55	-0.41	3.38	4.32	2,742.6	3,695.0
DCC column internals	A-101	SS304 (welded)	170.0	0.90	0.90	154.62	803.2	596.2	114.77	1.60	96.64	4.85	0.76	-1.05	3.80	4.85	468.8	631.6
Absorber column shell, nozzles & skirt	A-102	SS304 (welded)	1,475.0	0.90	0.75	1,362.93	803.2	596.2	1011.63	1.60	851.83	3.35	0.38	-0.29	3.05	3.88	3,307.5	4,456.1
Absorber column internals	A-102	SS304 (welded)	850.0	0.90	0.90	773.10	803.2	596.2	573.83	1.60	483.19	3.48	0.48	-0.72	2.77	3.65	1,765.7	2,378.8
Stripper column shell, nozzles & skirt	A-103	SS304 (welded)	900.0	0.90	0.75	831.62	803.2	596.2	617.26	1.60	519.76	3.86	0.48	-0.34	3.52	4.40	2,288.9	3,083.8
Stripper column internals	A-103	SS304 (welded)	240.0	0.90	0.90	218.29	803.2	596.2	162.02	1.60	136.43	4.85	0.76	-1.05	3.80	4.85	661.9	891.7
Fluegas blower	C-101A	SS304 (Machined)	75.3	0.91	0.75	70.16	803.2	596.2	52.07	1.20	58.46	6.94	0.96	-0.29	6.64	7.03	411.1	553.9
Fluegas blower	C-101B	SS304 (Machined)	75.3	0.91	0.75	70.16	803.2	596.2	52.07	1.20	58.46	6.94	0.96	-0.29	6.64	7.03	411.1	553.9
Fluegas blower	C-101C	SS304 (Machined)	75.3	0.91	0.75	70.16	803.2	596.2	52.07	1.20	58.46	6.94	0.96	-0.29	6.64	7.03	411.1	553.9
Flue gas boiler - steam/cond. Drum + internals	V-101	CS	31.9	1.00	0.75	31.90	803.2	596.2	23.68	1.00	31.90	8.02	1.41	-0.52	7.49	7.49	239.1	322.1
Flue gas boiler - steam/cond. Drum + internals	V-102	CS	33.9	1.00	0.75	33.90	803.2	596.2	25.16	1.00	33.90	8.02	1.41	-0.52	7.49	7.49	254.0	342.3
Flue gas boiler - steam/cond. Drum + internals	V-103	CS	42.0	1.00	0.75	42.00	803.2	596.2	31.17	1.00	42.00	6.78	1.11	-0.45	6.32	6.32	265.6	357.9
Flue gas boiler - steam/cond. Drum + internals	V-104	CS	32.3	1.00	0.75	32.30	803.2	596.2	23.97	1.00	32.30	8.02	1.41	-0.52	7.49	7.49	242.1	326.1
Flue gas boiler - steam/cond. Drum + internals	V-105	CS	36.8	1.00	0.75	36.80	803.2	596.2	27.31	1.00	36.80	8.02	1.41	-0.52	7.49	7.49	275.8	371.5
Flue gas boiler - steam/cond. Drum + internals	V-106A	CS	41.8	1.00	0.75	41.80	803.2	596.2	31.03	1.00	41.80	6.78	1.11	-0.45	6.32	6.32	264.4	356.2
Flue gas boiler - steam/cond. Drum + internals	V-106B	CS	41.8	1.00	0.75	41.80	803.2	596.2	31.03	1.00	41.80	6.78	1.11	-0.45	6.32	6.32	264.4	356.2
Flue gas boiler - steam/cond. Drum + internals	V-107	CS	39.3	1.00	0.75	39.30	803.2	596.2	29.17	1.00	39.30	8.02	1.41	-0.52	7.49	7.49	294.5	396.8
Flue gas boiler - steam/cond. Drum + internals	V-108	CS	30.8	1.00	0.75	30.80	803.2	596.2	22.86	1.00	30.80	8.02	1.41	-0.52	7.49	7.49	230.8	311.0
Flue gas boiler - steam/cond. Drum + internals	V-109	CS	28.2	1.00	0.75	28.20	803.2	596.2	20.93	1.00	28.20	8.02	1.41	-0.52	7.49	7.49	211.3	284.7
Flue gas boiler - steam/cond. Drum + internals	V-110A	CS	27.0	1.00	0.75	27.00	803.2	596.2	20.04	1.00	27.00	8.02	1.41	-0.52	7.49	7.49	202.3	272.6
Flue gas boiler - steam/cond. Drum + internals	V-110B	CS	27.0	1.00	0.75	27.00	803.2	596.2	20.04	1.00	27.00	8.02	1.41	-0.52	7.49	7.49	202.3	272.6
Amine act. Carbon filter + particle filter	F-101A	CS	142.0	0.90	0.75	131.21	803.2	596.2	97.39	1.00	131.21	5.00	0.76	-0.90	4.10	4.10	538.1	724.9
Amine act. Carbon filter + particle filter	F-101B	CS	142.0	0.90	0.75	131.21	803.2	596.2	97.39	1.00	131.21	5.00	0.76	-0.90	4.10	4.10	538.1	724.9
Stripper reflux drum	V-112	SS304 (welded)	52.8	0.90	0.75	48.79	803.2	596.2	36.21	1.60	30.49	7.83	1.22	-0.71	7.11	8.44	257.5	346.9
LP steam condensate collection drum	V-121	CS	36.0	0.90	0.75	33.26	803.2	596.2	24.69	1.00	33.26	7.83	1.22	-0.71	7.11	7.11	236.6	318.8
Flue gas boiler - heat exchanger	E-101	SS304 (welded)	70.7	1.00	0.75	70.70	803.2	596.2	52.48	1.60	44.19	6.78	1.11	-0.45	6.32	7.59	335.4	451.9
Flue gas boiler - heat exchanger	E-102	SS304 (welded)	102.6	1.00	0.75	102.60	803.2	596.2	76.15	1.60	64.13	6.78	1.11	-0.45	6.32	7.59	486.8	655.8
Flue gas boiler - heat exchanger	E-103	SS304 (welded)	159.2	1.00	0.75	159.20	803.2	596.2	118.17	1.60	99.50	5.51	0.88	-0.39	5.12	6.24	621.2	836.9
Flue gas boiler - heat exchanger	E-104	SS304 (welded)	73.8	1.00	0.75	73.80	803.2	596.2	54.78	1.60	46.13	6.78	1.11	-0.45	6.32	7.59	350.1	471.7
Flue gas boiler - heat exchanger	E-105	SS304 (welded)	116.2	1.00	0.75	116.20	803.2	596.2	86.25	1.60	72.63	6.78	1.11	-0.45	6.32	7.59	551.3	742.7
Flue gas boiler - heat exchanger	E-106A	SS304 (welded)	167.0	1.00	0.75	167.00	803.2	596.2	123.95	1.60	104.38	5.51	0.88	-0.39	5.12	6.24	651.6	877.9
Flue gas boiler - heat exchanger	E-106B	SS304 (welded)	167.0	1.00	0.75	167.00	803.2	596.2	123.95	1.60	104.38	5.51	0.88	-0.39	5.12	6.24	651.6	877.9
Flue gas boiler - heat exchanger	E-107	SS304 (welded)	176.5	1.00	0.75	176.50	803.2	596.2	131.01	1.60	110.31	5.51	0.88	-0.39	5.12	6.24	688.7	927.8
Flue gas boiler - heat exchanger	E-108	SS304 (welded)	62.6	1.00	0.75	62.60	803.2	596.2	46.46	1.60	39.13	8.02	1.41	-0.52	7.49	8.94	349.8	471.3
Flue gas boiler - heat exchanger	E-109	SS304 (welded)	36.9	1.00	0.75	36.90	803.2	596.2	27.39	1.60	23.06	8.02	1.41	-0.52	7.49	8.94	206.2	277.8
Flue gas boiler - heat exchanger	E-110A	SS304 (welded)	36.0	1.00	0.75	36.00	803.2	596.2	26.72	1.60	22.50	8.02	1.41	-0.52	7.49	8.94	201.2	271.0
Flue gas boiler - heat exchanger	E-110B	SS304 (welded)	36.0	1.00	0.75	36.00	803.2	596.2	26.72	1.60	22.50	8.02	1.41	-0.52	7.49	8.94	201.2	271.0
Stripper reboiler	E-116A	SS304 (welded)	534.1	0.90	1.00	480.69	803.2	596.2	356.79	1.60	300.43	4.49	0.60	-0.43	4.06	5.02	1,508.2	2,031.9
Stripper reboiler	E-116B	SS304 (welded)	534.1	0.90	1.00	480.69	803.2	596.2	356.79	1.60	300.43	4.49	0.60	-0.43	4.06	5.02	1,508.2	2,031.9
DCC water circulation cooler	E-111	SS316 (welded)	234.0	0.90	1.00	210.60	803.2	596.2	156.32	1.75	120.34	5.39	0.76	-0.51	4.88	6.20	745.9	1,004.9
Amine cooler	E-112	SS316 (welded)	47.3	0.90	1.00	42.57	803.2	596.2	31.60	1.75	24.33	7.83	1.22	-0.71	7.11	8.78	213.5	287.7
Combined amine cooler / heater	E-113	SS316 (welded)	381.2	0.90	1.00	343.08	803.2	596.2	254.65	1.75	196.05	4.49	0.60	-0.43	4.06	5.26	1,031.2	1,389.3
Absorber top cooler	E-114	SS316 (welded)	107.9	0.90	1.00	97.11	803.2	596.2	72.08	1.75	55.49	6.50	0.96	-0.73	5.78	7.25	402.2	541.9
Stripper condenser	E-115	SS316 (welded)	62.9	0.90	0.75	58.12	803.2	596.2	43.14	1.75	33.21	7.83	1.22	-0.71	7.11	8.78	291.5	392.7
DCC circulation pump + motor	P-101A	SS316 (Machined)	43.1	0.85	0.75	38.15	803.2	596.2	28.32	1.30	29.35	8.17	1.22	-0.37	7.81	8.47	248.6	335.0
DCC circulation pump + motor	P-101B	SS316 (Machined)	43.1	0.85	0.75	38.15	803.2	596.2	28.32	1.30	29.35	8.17	1.22	-0.37	7.81	8.47	248.6	335.0
DCC circulation pump + motor	P-101S	SS316 (Machined)	43.1	0.85	0.75	38.15	803.2	596.2	28.32	1.30	29.35	8.17	1.22	-0.37	7.81	8.47	248.6	335.0
Rich amine pump + motor	P-102A	SS316 (Machined)	30.3	0.90	0.75	28.00	803.2	596.2	20.78	1.30	21.54	8.33	1.22	-0.21	8.13	8.79	189.4	255.2
Rich amine pump + motor	P-102B	SS316 (Machined)	30.3	0.90	0.75	28.00	803.2	596.2	20.78	1.30	21.54	8.33	1.22	-0.21	8.13	8.79	189.4	255.2
Rich amine pump + motor	P-102S	SS316 (Machined)	30.3	0.90	0.75	28.00	803.2	596.2	20.78	1.30	21.54	8.33	1.22	-0.21	8.13	8.79	189.4	255.2
Lean amine pump + motor	P-103A	SS316 (Machined)	29.8	0.90	0.75	27.54	803.2	596.2	20.44	1.30	21.18	8.33	1.22	-0.21	8.13	8.79	186.3	251.0
Lean amine pump + motor	P-103B	SS316 (Machined)	29.8	0.90	0.75	27.54	803.2	596.2	20.44	1.30	21.18	8.33	1.22	-0.21	8.13	8.79	186.3	251.0
Lean amine pump + motor	P-103S	SS316 (Machined)	29.8	0.90	0.75	27.54	803.2	596.2	20.44	1.30	21.18	8.33	1.22	-0.21	8.13	8.79	186.3	251.0
Wash water circulation pump + motor	P-104A	SS316 (Machined)	37.6	0.90	0.75	34.74	803.2	596.2	25.79	1.30	26.73	8.17	1.22	-0.37	7.81	8.47	226.4	305.0
Wash water circulation pump + motor	P-104B	SS316 (Machined)	37.6	0.90	0.75	34.74	803.2	596.2	25.79	1.30	26.73	8.17	1.22	-0.37	7.81	8.47	226.4	305.0
Wash water circulation pump + motor	P-104S	SS316 (Machined)	37.6	0.90	0.75	34.74	803.2	596.2	25.79	1.30	26.73	8.17	1.22	-0.37	7.81	8.47	226.4	305.0
Stripper reflux pump + motor	P-105A	SS316 (Machined)	6.9	0.90	0.75	6.38	803.2	596.2	4.73	1.30	4.90	14.67	2.24	-0.35	14.31	15.28	75.0	101.0
Stripper reflux pump + motor	P-105S	SS316 (Machined)	6.9	0.90	0.75	6.38	803.2	596.2	4.73	1.30	4.90	14.67	2.24	-0.35	14.31	15.28	75.0	101.0
LP steam condensate pumps	P-121A	SS316 (Machined)	14.2	0.90	0.75	13.07	803.2	596.2	9.70	1.30	10.06	9.87	1.54	-0.26	9.61	10.37	104.3	140.5
LP steam condensate pumps	P-121S	SS316 (Machined)	14.2	0.90	0.75	13.07	803.2	596.2	9.70	1.30	10.06	9.87	1.54	-0.26	9.61	10.37	104.3	140.5
Cooling water circulation pump	P-401A	CS	70.0	0.90	0.75	64.68	803.2	596.2	48.01	1.00	64.68	6.94	0.96	-0.29	6.64	6.64	429.5	578.6
Cooling water circulation pump	P-401B	CS	70.0	0.90	0.75	64.68	803.2	596.2	48.01	1.00	64.68	6.94	0.96	-0.29	6.64	6.64	429.5	578.6
Cooling water circulation pump	P-401C	CS	70.0	0.90	0.75	64.68	803.2	596.2	48.01	1.00	64.68	6.94	0.96	-0.29	6.64	6.64	429.5	578.6
Cooling water circulation pump	P-401S	CS	70.0	0.90	0.75	64.68	803.2	596.2	48.01	1.00	64.68	6.94	0.96	-0.29	6.64	6.64	429.5	578.6
Cooling water dry-cooler	E-401	CS	4,600.0	0.90	0.80	4,228.16	803.2	596.2	3138.33	1.00	4228.16	2.75	0.23	-0.08	2.68	2.68	11,326.4	15,259.7
Natural gas fired steam boiler unit	X-101	CS	382.6	0.00	1.00	0.00	803.2	596.2	0.00	1.00	0.00	13.12	2.24	-1.90	11.22	11.22	0.0	0.0
Amine reclaimer unit	X-102	CS	335.0	0.90	0.75	309.55	803.2	596.2	229.76	1.00	309.55	3.72	-0.11	-1.19	2.52	2.52	780.1	1,051.0
Amine solvent supply system	X-103	SS304 (welded)	20.0	0.90	0.65	18.68	803.2	596.2	13.86	1.60	11.67	9.57	1.54	-0.55	9.03	10.55	123.1	165.9
Total equipment cost (TEC) & Total plant cost (TPC), k€		k€	14,934.60			13,481.40										4.05	44,839.7	60,411.0

Table 6.4.2. Total Installed Plant (TPC) cost MEA Case B

EDF method - Costing sheet - HS3 Case A Equipment	Tag. No.	Material	2023 price Cost per Unit, k€	2023 price Cost per Unit, k€	CEPSI apr-23	CEPSI 2020	2020 price Cost per Unit, k€	Mat'l factor	Cost in CS k€	Std. Inst. fact. (CS)	Piping factor	PCCF corr.	PCCF corr. Inst. fact. (CS)	Total Act. Inst. factor	2020 Total Inst. Cost, k€	2023 Total Inst. Cost, k€
DCC column shell, nozzles & skirt	A-101	SS304 (welded)	1.100,00	1.100,00	803,2	596,2	816,47	1,60	687,50	3,28	0,44	-0,36	2,92	3,79	2.604,2	3.508,5
DCC column internals	A-101	SS304 (welded)	170,00	170,00	803,2	596,2	126,18	1,60	106,25	4,85	0,76	-1,05	3,80	4,85	515,5	694,5
Absorber column shell, nozzles & skirt	A-102	SS304 (welded)	1.737,50	1.737,50	803,2	596,2	1289,65	1,60	1085,94	3,35	0,38	-0,29	3,05	3,88	4.216,5	5.680,7
Absorber column internals	A-102	SS304 (welded)	950,00	950,00	803,2	596,2	705,13	1,60	593,75	3,48	0,48	-0,72	2,77	3,65	2.169,7	2.923,1
Stripper column shell, nozzles & skirt	A-103	SS304 (welded)	750,00	750,00	803,2	596,2	556,68	1,60	468,75	3,86	0,48	-0,34	3,52	4,40	2.064,3	2.781,1
Stripper column internals	A-103	SS304 (welded)	280,00	280,00	803,2	596,2	207,83	1,60	175,00	4,06	0,60	-0,85	3,21	4,17	730,1	983,6
Fluegas blower	C-101A	SS304 (Machined)	72,80	72,80	803,2	596,2	54,04	1,20	60,67	6,94	0,96	-0,29	6,64	7,03	426,6	574,8
Fluegas blower	C-101B	SS304 (Machined)	72,80	72,80	803,2	596,2	54,04	1,20	60,67	6,94	0,96	-0,29	6,64	7,03	426,6	574,8
Fluegas blower	C-101C	SS304 (Machined)	72,80	72,80	803,2	596,2	54,04	1,20	60,67	6,94	0,96	-0,29	6,64	7,03	426,6	574,8
Flue gas boiler - steam/cond. Drum + internals	V-101	CS	31,90	31,90	803,2	596,2	23,68	1,00	31,90	8,02	1,41	-0,52	7,49	7,49	239,1	322,1
Flue gas boiler - steam/cond. Drum + internals	V-102	CS	33,90	33,90	803,2	596,2	25,16	1,00	33,90	8,02	1,41	-0,52	7,49	7,49	254,0	342,3
Flue gas boiler - steam/cond. Drum + internals	V-103	CS	42,00	42,00	803,2	596,2	31,17	1,00	42,00	6,78	1,11	-0,45	6,32	6,32	265,6	357,9
Flue gas boiler - steam/cond. Drum + internals	V-104	CS	32,30	32,30	803,2	596,2	23,97	1,00	32,30	8,02	1,41	-0,52	7,49	7,49	242,1	326,1
Flue gas boiler - steam/cond. Drum + internals	V-105	CS	36,80	36,80	803,2	596,2	27,31	1,00	36,80	8,02	1,41	-0,52	7,49	7,49	275,8	371,5
Flue gas boiler - steam/cond. Drum + internals	V-106A	CS	41,80	41,80	803,2	596,2	31,03	1,00	41,80	6,78	1,11	-0,45	6,32	6,32	264,4	356,2
Flue gas boiler - steam/cond. Drum + internals	V-106B	CS	41,80	41,80	803,2	596,2	31,03	1,00	41,80	6,78	1,11	-0,45	6,32	6,32	264,4	356,2
Flue gas boiler - steam/cond. Drum + internals	V-107	CS	39,30	39,30	803,2	596,2	29,17	1,00	39,30	8,02	1,41	-0,52	7,49	7,49	294,5	396,8
Flue gas boiler - steam/cond. Drum + internals	V-108	CS	30,80	30,80	803,2	596,2	22,86	1,00	30,80	8,02	1,41	-0,52	7,49	7,49	230,8	311,0
Flue gas boiler - steam/cond. Drum + internals	V-109	CS	28,20	28,20	803,2	596,2	20,93	1,00	28,20	8,02	1,41	-0,52	7,49	7,49	211,3	284,7
Flue gas boiler - steam/cond. Drum + internals	V-110A	CS	27,00	27,00	803,2	596,2	20,04	1,00	27,00	8,02	1,41	-0,52	7,49	7,49	202,3	272,6
Flue gas boiler - steam/cond. Drum + internals	V-110B	CS	27,00	27,00	803,2	596,2	20,04	1,00	27,00	8,02	1,41	-0,52	7,49	7,49	202,3	272,6
Amine act. Carbon filter + particle filter + fillings	F-101A	CS	117,80	117,80	803,2	596,2	87,44	1,00	117,80	5,00	0,76	-0,90	4,10	4,10	483,1	650,8
Amine act. Carbon filter + particle filter + fillings	F-101B	CS	117,80	117,80	803,2	596,2	87,44	1,00	117,80	5,00	0,76	-0,90	4,10	4,10	483,1	650,8
Stripper reflux drum	V-112	SS304 (welded)	52,80	52,80	803,2	596,2	39,19	1,60	33,00	7,83	1,22	-0,71	7,11	8,44	278,7	375,4
LP steam condensate collection drum	V-121	CS	31,80	31,80	803,2	596,2	23,60	1,00	31,80	7,83	1,22	-0,71	7,11	7,11	226,2	304,7
Flue gas boiler - heat exchanger	E-101	SS304 (welded)	70,70	70,70	803,2	596,2	52,48	1,60	44,19	6,78	1,11	-0,45	6,32	7,59	335,4	451,9
Flue gas boiler - heat exchanger	E-102	SS304 (welded)	102,60	102,60	803,2	596,2	76,15	1,60	64,13	6,78	1,11	-0,45	6,32	7,59	486,8	655,8
Flue gas boiler - heat exchanger	E-103	SS304 (welded)	159,20	159,20	803,2	596,2	118,17	1,60	99,50	5,51	0,88	-0,39	5,12	6,24	621,2	836,9
Flue gas boiler - heat exchanger	E-104	SS304 (welded)	73,80	73,80	803,2	596,2	54,78	1,60	46,13	6,78	1,11	-0,45	6,32	7,59	350,1	471,7
Flue gas boiler - heat exchanger	E-105	SS304 (welded)	116,20	116,20	803,2	596,2	86,25	1,60	72,63	6,78	1,11	-0,45	6,32	7,59	551,3	742,7
Flue gas boiler - heat exchanger	E-106A	SS304 (welded)	167,00	167,00	803,2	596,2	123,95	1,60	104,38	5,51	0,88	-0,39	5,12	6,24	651,6	877,9
Flue gas boiler - heat exchanger	E-106B	SS304 (welded)	167,00	167,00	803,2	596,2	123,95	1,60	104,38	5,51	0,88	-0,39	5,12	6,24	651,6	877,9
Flue gas boiler - heat exchanger	E-107	SS304 (welded)	176,50	176,50	803,2	596,2	131,01	1,60	110,31	5,51	0,88	-0,39	5,12	6,24	688,7	927,8
Flue gas boiler - heat exchanger	E-108	SS304 (welded)	62,60	62,60	803,2	596,2	46,46	1,60	39,13	8,02	1,41	-0,52	7,49	8,94	349,8	471,3
Flue gas boiler - heat exchanger	E-109	SS304 (welded)	36,90	36,90	803,2	596,2	27,39	1,60	23,06	8,02	1,41	-0,52	7,49	8,94	206,2	277,8
Flue gas boiler - heat exchanger	E-110A	SS304 (welded)	36,00	36,00	803,2	596,2	26,72	1,60	22,50	8,02	1,41	-0,52	7,49	8,94	201,2	271,0
Flue gas boiler - heat exchanger	E-110B	SS304 (welded)	36,00	36,00	803,2	596,2	26,72	1,60	22,50	8,02	1,41	-0,52	7,49	8,94	201,2	271,0
Stripper reboiler	E-116A	SS304 (welded)	810,90	810,90	803,2	596,2	601,89	1,60	506,81	3,83	0,48	-0,37	3,47	4,35	2.206,4	2.972,5
Stripper reboiler	E-116B	SS304 (welded)	810,90	810,90	803,2	596,2	601,89	1,60	506,81	3,83	0,48	-0,37	3,47	4,35	2.206,4	2.972,5
DCC water circulation cooler	E-111	SS316 (welded)	234,00	234,00	803,2	596,2	173,69	1,75	133,71	5,39	0,76	-0,51	4,88	6,20	828,8	1.116,6
Amine cooler	E-112	SS316 (welded)	60,30	60,30	803,2	596,2	44,76	1,75	34,46	7,83	1,22	-0,71	7,11	8,78	302,4	407,5
Combined amine cooler / heater	E-113	SS316 (welded)	631,80	631,80	803,2	596,2	468,95	1,75	361,03	3,83	0,48	-0,37	3,47	4,58	1.651,9	2.225,5
Absorber top cooler	E-114	SS316 (welded)	78,00	78,00	803,2	596,2	57,90	1,75	44,57	6,50	0,96	-0,73	5,78	7,25	323,0	435,2
Stripper condenser	E-115	SS316 (welded)	59,60	59,60	803,2	596,2	44,24	1,75	34,06	7,83	1,22	-0,71	7,11	8,78	298,9	402,7
DCC circulation pump + motor	P-101A	SS316 (Machined)	43,10	43,10	803,2	596,2	31,99	1,30	33,15	8,17	1,22	-0,37	7,81	8,47	280,9	378,4
DCC circulation pump + motor	P-101B	SS316 (Machined)	43,10	43,10	803,2	596,2	31,99	1,30	33,15	8,17	1,22	-0,37	7,81	8,47	280,9	378,4
DCC circulation pump + motor	P-101S	SS316 (Machined)	43,10	43,10	803,2	596,2	31,99	1,30	33,15	8,17	1,22	-0,37	7,81	8,47	280,9	378,4
Rich amine pump + motor	P-102A	SS316 (Machined)	23,80	23,80	803,2	596,2	17,67	1,30	18,31	9,87	1,54	-0,26	9,61	10,37	189,9	255,8
Rich amine pump + motor	P-102B	SS316 (Machined)	23,80	23,80	803,2	596,2	17,67	1,30	18,31	9,87	1,54	-0,26	9,61	10,37	189,9	255,8
Rich amine pump + motor	P-102S	SS316 (Machined)	23,80	23,80	803,2	596,2	17,67	1,30	18,31	9,87	1,54	-0,26	9,61	10,37	189,9	255,8
Lean amine pump + motor	P-103A	SS316 (Machined)	25,10	25,10	803,2	596,2	18,63	1,30	19,31	9,87	1,54	-0,26	9,61	10,37	200,3	269,8
Lean amine pump + motor	P-103B	SS316 (Machined)	25,10	25,10	803,2	596,2	18,63	1,30	19,31	9,87	1,54	-0,26	9,61	10,37	200,3	269,8
Lean amine pump + motor	P-103S	SS316 (Machined)	25,10	25,10	803,2	596,2	18,63	1,30	19,31	9,87	1,54	-0,26	9,61	10,37	200,3	269,8
Wash water circulation pump + motor	P-104A	SS316 (Machined)	22,80	22,80	803,2	596,2	16,92	1,30	17,54	9,66	1,54	-0,46	9,19	9,95	174,6	235,2
Wash water circulation pump + motor	P-104B	SS316 (Machined)	22,80	22,80	803,2	596,2	16,92	1,30	17,54	9,66	1,54	-0,46	9,19	9,95	174,6	235,2
Wash water circulation pump + motor	P-104S	SS316 (Machined)	22,80	22,80	803,2	596,2	16,92	1,30	17,54	9,66	1,54	-0,46	9,19	9,95	174,6	235,2
Stripper reflux pump + motor	P-105A	SS316 (Machined)	8,81	8,81	803,2	596,2	6,54	1,30	6,78	14,67	2,24	-0,35	14,31	15,28	103,6	139,5
Stripper reflux pump + motor	P-105S	SS316 (Machined)	8,81	8,81	803,2	596,2	6,54	1,30	6,78	14,67	2,24	-0,35	14,31	15,28	103,6	139,5
LP steam condensate pump	P-121A	SS316 (Machined)	9,85	9,85	803,2	596,2	7,31	1,30	7,58	14,67	2,24	-0,35	14,31	15,28	115,8	156,0
LP steam condensate pump	P-121S	SS316 (Machined)	9,85	9,85	803,2	596,2	7,31	1,30	7,58	14,67	2,24	-0,35	14,31	15,28	115,8	156,0
Cooling water circulation pump	P-401A	CS	70,00	70,00	803,2	596,2	51,96	1,00	70,00	6,94	0,96	-0,29	6,64	6,64	464,8	626,2
Cooling water circulation pump	P-401B	CS	70,00	70,00	803,2	596,2	51,96	1,00	70,00	6,94	0,96	-0,29	6,64	6,64	464,8	626,2
Cooling water circulation pump	P-401C	CS	70,00	70,00	803,2	596,2	51,96	1,00	70,00	6,94	0,96	-0,29	6,64	6,64	464,8	626,2
Cooling water circulation pump	P-401S	CS	70,00	70,00	803,2	596,2	51,96	1,00	70,00	6,94	0,96	-0,29	6,64	6,64	464,8	626,2
Cooling water dry-cooler	E-401	CS	4.300,00	4.300,00	803,2	596,2	3191,65	1,00	4300,00	2,75	0,23	-0,08	2,68	2,68	11.518,8	15.518,9
Natural gas fired steam boiler unit	X-101	CS	382,60	382,60	803,2	596,2	283,98	1,00	382,60	3,80	0,48	-0,40	3,40	3,40	1.302,1	1.754,2
Amine reclaimer unit	X-102	SS316 (welded)	335,00	335,00	803,2	596,2	248,65	1,75	191,43	3,72	-0,11	-1,19	2,52	3,19	610,2	822,2
Amine solvent supply system	X-103	SS304 (welded)	10,00	10,00	803,2	596,2	7,42	1,60	6,25	14,21	2,24	-0,81	13,40	15,34	95,9	129,2
Total equipment cost (TEC) & Total plant cost (TPC), k€		k€		**15.518,22**										**4,30**	**49.472,2**	**66.652,1**

Table 6.4.3. Total Installed Plant (TPC) cost HS3 Case A

EDF method - Costing sheet - HS3 Case B			HS3 Case A 2023 price Cost per Unit, k€	HS3 Case A 2023 price Cost per Unit, k€	HS3 Case B Cap. Factor	Cost Scale exp.	HS3 Case B 2023 price Cost per Unit, k€	CEPSI apr-23	CEPSI 2020	2020 price Cost per Unit, k€	Mat'l factor	Cost in CS k€	Std. Inst. fact. (CS)	Piping factor	PCCF corr.	PCCF Corr. Inst. fact. (CS)	Total Act. Inst. factor	2020 Total Inst. Cost, k€	2023 Total Inst. Cost, k€
Equipment	Tag. No.	Material																	
DCC column shell, nozzles & skirt	A-101	SS304 (welded)	1.100,00	1.100,00	0,95	0,75	1.058,49	803,2	596,2	785,66	1,60	661,55	3,28	0,44	-0,36	2,92	3,79	2.505,9	3.376,1
DCC column internals	A-101	SS304 (welded)	170,00	170,00	0,95	0,90	162,33	803,2	596,2	120,49	1,60	101,46	4,85	0,76	-1,05	3,80	4,85	492,2	663,1
Absorber column shell, nozzles & skirt	A-102	SS304 (welded)	1.737,50	1.737,50	0,95	0,75	1.671,93	803,2	596,2	1240,98	1,60	1044,95	3,35	0,38	-0,29	3,05	3,88	4.057,4	5.466,3
Absorber column internals	A-102	SS304 (welded)	950,00	950,00	0,95	0,90	907,14	803,2	596,2	673,32	1,60	566,96	3,48	0,48	-0,72	2,77	3,65	2.071,8	2.791,3
Stripper column shell, nozzles & skirt	A-103	SS304 (welded)	750,00	750,00	0,95	0,75	721,70	803,2	596,2	535,67	1,60	451,06	3,86	0,48	-0,34	3,52	4,40	1.986,4	2.676,2
Stripper column internals	A-103	SS304 (welded)	280,00	280,00	0,95	0,90	267,37	803,2	596,2	198,45	1,60	167,10	4,06	0,60	-0,85	3,21	4,17	697,1	939,2
Fluegas blower	C-101A	SS304 (Machined)	72,80	72,80	0,95	0,75	70,05	803,2	596,2	52,00	1,20	58,38	6,94	0,96	-0,29	6,64	7,03	410,5	553,1
Fluegas blower	C-101B	SS304 (Machined)	72,80	72,80	0,95	0,75	70,05	803,2	596,2	52,00	1,20	58,38	6,94	0,96	-0,29	6,64	7,03	410,5	553,1
Fluegas blower	C-101C	SS304 (Machined)	72,80	72,80	0,95	0,75	70,05	803,2	596,2	52,00	1,20	58,38	6,94	0,96	-0,29	6,64	7,03	410,5	553,1
Flue gas boiler - steam/cond. Drum + internals	V-101	CS	31,90	31,90	1,00	0,75	31,90	803,2	596,2	23,68	1,00	31,90	8,02	1,41	-0,52	7,49	7,49	239,1	322,1
Flue gas boiler - steam/cond. Drum + internals	V-102	CS	33,90	33,90	1,00	0,75	33,90	803,2	596,2	25,16	1,00	33,90	8,02	1,41	-0,52	7,49	7,49	254,0	342,3
Flue gas boiler - steam/cond. Drum + internals	V-103	CS	42,00	42,00	1,00	0,75	42,00	803,2	596,2	31,17	1,00	42,00	6,78	1,11	-0,45	6,32	6,32	265,6	357,9
Flue gas boiler - steam/cond. Drum + internals	V-104	CS	32,30	32,30	1,00	0,75	32,30	803,2	596,2	23,97	1,00	32,30	8,02	1,41	-0,52	7,49	7,49	242,1	326,1
Flue gas boiler - steam/cond. Drum + internals	V-105	CS	36,80	36,80	1,00	0,75	36,80	803,2	596,2	27,31	1,00	36,80	8,02	1,41	-0,52	7,49	7,49	275,8	371,5
Flue gas boiler - steam/cond. Drum + internals	V-106A	CS	41,80	41,80	1,00	0,75	41,80	803,2	596,2	31,03	1,00	41,80	6,78	1,11	-0,45	6,32	6,32	264,4	356,2
Flue gas boiler - steam/cond. Drum + internals	V-106B	CS	41,80	41,80	1,00	0,75	41,80	803,2	596,2	31,03	1,00	41,80	6,78	1,11	-0,45	6,32	6,32	264,4	356,2
Flue gas boiler - steam/cond. Drum + internals	V-107	CS	39,30	39,30	1,00	0,75	39,30	803,2	596,2	29,17	1,00	39,30	8,02	1,41	-0,52	7,49	7,49	294,5	396,8
Flue gas boiler - steam/cond. Drum + internals	V-108	CS	30,80	30,80	1,00	0,75	30,80	803,2	596,2	22,86	1,00	30,80	8,02	1,41	-0,52	7,49	7,49	230,8	311,0
Flue gas boiler - steam/cond. Drum + internals	V-109	CS	28,20	28,20	1,00	0,75	28,20	803,2	596,2	20,93	1,00	28,20	8,02	1,41	-0,52	7,49	7,49	211,3	284,7
Flue gas boiler - steam/cond. Drum + internals	V-110A	CS	27,00	27,00	1,00	0,75	27,00	803,2	596,2	20,04	1,00	27,00	8,02	1,41	-0,52	7,49	7,49	202,3	272,6
Flue gas boiler - steam/cond. Drum + internals	V-110B	CS	27,00	27,00	1,00	0,75	27,00	803,2	596,2	20,04	1,00	27,00	8,02	1,41	-0,52	7,49	7,49	202,3	272,6
Amine act. Carbon filter + particle filter + fillings	F-101A	CS	117,80	117,80	0,95	0,75	113,35	803,2	596,2	84,14	1,00	113,35	5,00	0,76	-0,90	4,10	4,10	464,8	626,3
Amine act. Carbon filter + particle filter + fillings	F-101B	CS	117,80	117,80	0,95	0,75	113,35	803,2	596,2	84,14	1,00	113,35	5,00	0,76	-0,90	4,10	4,10	464,8	626,3
Stripper reflux drum	V-112	SS304 (welded)	52,80	52,80	0,95	0,75	50,81	803,2	596,2	37,71	1,60	31,75	7,83	1,22	-0,71	7,11	8,44	268,1	361,3
LP steam condensate collection drum	V-121	CS	31,80	31,80	1,00	0,75	31,80	803,2	596,2	23,60	1,00	31,80	7,83	1,22	-0,71	7,11	7,11	226,2	304,7
Flue gas boiler - heat exchanger	E-101	SS304 (welded)	70,70	70,70	1,00	0,75	70,70	803,2	596,2	52,48	1,60	44,19	6,78	1,11	-0,45	6,32	7,59	335,4	451,9
Flue gas boiler - heat exchanger	E-102	SS304 (welded)	102,60	102,60	1,00	0,75	102,60	803,2	596,2	76,15	1,60	64,13	6,78	1,11	-0,45	6,32	7,59	486,8	655,8
Flue gas boiler - heat exchanger	E-103	SS304 (welded)	159,20	159,20	1,00	0,75	159,20	803,2	596,2	118,17	1,60	99,50	5,51	0,88	-0,39	5,12	6,24	621,2	836,9
Flue gas boiler - heat exchanger	E-104	SS304 (welded)	73,80	73,80	1,00	0,75	73,80	803,2	596,2	54,78	1,60	46,13	6,78	1,11	-0,45	6,32	7,59	350,1	471,7
Flue gas boiler - heat exchanger	E-105	SS304 (welded)	116,20	116,20	1,00	0,75	116,20	803,2	596,2	86,25	1,60	72,63	6,78	1,11	-0,45	6,32	7,59	551,3	742,7
Flue gas boiler - heat exchanger	E-106A	SS304 (welded)	167,00	167,00	1,00	0,75	167,00	803,2	596,2	123,95	1,60	104,38	5,51	0,88	-0,39	5,12	6,24	651,6	877,9
Flue gas boiler - heat exchanger	E-106B	SS304 (welded)	167,00	167,00	1,00	0,75	167,00	803,2	596,2	123,95	1,60	104,38	5,51	0,88	-0,39	5,12	6,24	651,6	877,9
Flue gas boiler - heat exchanger	E-107	SS304 (welded)	176,50	176,50	1,00	0,75	176,50	803,2	596,2	131,01	1,60	110,31	5,51	0,88	-0,39	5,12	6,24	688,7	927,8
Flue gas boiler - heat exchanger	E-108	SS304 (welded)	62,60	62,60	1,00	0,75	62,60	803,2	596,2	46,46	1,60	39,13	8,02	1,41	-0,52	7,49	8,94	349,8	471,3
Flue gas boiler - heat exchanger	E-109	SS304 (welded)	36,90	36,90	1,00	0,75	36,90	803,2	596,2	27,39	1,60	23,06	8,02	1,41	-0,52	7,49	8,94	206,2	277,8
Flue gas boiler - heat exchanger	E-110A	SS304 (welded)	36,00	36,00	1,00	0,75	36,00	803,2	596,2	26,72	1,60	22,50	8,02	1,41	-0,52	7,49	8,94	201,2	271,0
Flue gas boiler - heat exchanger	E-110B	SS304 (welded)	36,00	36,00	1,00	0,75	36,00	803,2	596,2	26,72	1,60	22,50	8,02	1,41	-0,52	7,49	8,94	201,2	271,0
Stripper reboiler	E-116A	SS304 (welded)	810,90	810,90	0,95	1,00	770,36	803,2	596,2	571,79	1,60	481,47	3,83	0,48	-0,37	3,47	4,35	2.096,0	2.823,9
Stripper reboiler	E-116B	SS304 (welded)	810,90	810,90	0,95	1,00	770,36	803,2	596,2	571,79	1,60	481,47	3,83	0,48	-0,37	3,47	4,35	2.096,0	2.823,9
DCC water circulation cooler	E-111	SS316 (welded)	234,00	234,00	0,96	1,00	224,64	803,2	596,2	166,74	1,75	128,37	5,39	0,76	-0,51	4,88	6,20	795,6	1.071,9
Amine cooler	E-112	SS316 (welded)	60,30	60,30	0,95	1,00	57,29	803,2	596,2	42,52	1,75	32,73	7,83	1,22	-0,71	7,11	8,78	287,3	387,1
Combined amine cooler / heater	E-113	SS316 (welded)	631,80	631,80	0,95	1,00	600,21	803,2	596,2	445,50	1,75	342,98	3,83	0,48	-0,37	3,47	4,58	1.569,3	2.114,2
Absorber top cooler	E-114	SS316 (welded)	78,00	78,00	0,95	1,00	74,10	803,2	596,2	55,00	1,75	42,34	6,50	0,96	-0,73	5,78	7,25	306,9	413,5
Stripper condenser	E-115	SS316 (welded)	59,60	59,60	0,95	0,75	57,35	803,2	596,2	42,57	1,75	32,77	7,83	1,22	-0,71	7,11	8,78	287,7	387,5
DCC circulation pump + motor	P-101A	SS316 (Machined)	43,10	43,10	0,95	0,75	41,47	803,2	596,2	30,78	1,30	31,90	8,17	1,22	-0,37	7,81	8,47	270,3	364,1
DCC circulation pump + motor	P-101B	SS316 (Machined)	43,10	43,10	0,95	0,75	41,47	803,2	596,2	30,78	1,30	31,90	8,17	1,22	-0,37	7,81	8,47	270,3	364,1
DCC circulation pump + motor	P-101S	SS316 (Machined)	43,10	43,10	0,95	0,75	41,47	803,2	596,2	30,78	1,30	31,90	8,17	1,22	-0,37	7,81	8,47	270,3	364,1
Rich amine pump + motor	P-102A	SS316 (Machined)	23,80	23,80	0,95	0,75	22,90	803,2	596,2	17,00	1,30	17,62	9,87	1,54	-0,26	9,61	10,37	182,7	246,2
Rich amine pump + motor	P-102B	SS316 (Machined)	23,80	23,80	0,95	0,75	22,90	803,2	596,2	17,00	1,30	17,62	9,87	1,54	-0,26	9,61	10,37	182,7	246,2
Rich amine pump + motor	P-102S	SS316 (Machined)	23,80	23,80	0,95	0,75	22,90	803,2	596,2	17,00	1,30	17,62	9,87	1,54	-0,26	9,61	10,37	182,7	246,2
Lean amine pump + motor	P-103A	SS316 (Machined)	25,10	25,10	0,95	0,75	24,15	803,2	596,2	17,93	1,30	18,58	9,87	1,54	-0,26	9,61	10,37	192,7	259,6
Lean amine pump + motor	P-103B	SS316 (Machined)	25,10	25,10	0,95	0,75	24,15	803,2	596,2	17,93	1,30	18,58	9,87	1,54	-0,26	9,61	10,37	192,7	259,6
Lean amine pump + motor	P-103S	SS316 (Machined)	25,10	25,10	0,95	0,75	24,15	803,2	596,2	17,93	1,30	18,58	9,87	1,54	-0,26	9,61	10,37	192,7	259,6
Wash water circulation pump + motor	P-104A	SS316 (Machined)	22,80	22,80	0,95	0,75	21,94	803,2	596,2	16,28	1,30	16,88	9,66	1,54	-0,46	9,19	9,95	168,0	226,3
Wash water circulation pump + motor	P-104B	SS316 (Machined)	22,80	22,80	0,95	0,75	21,94	803,2	596,2	16,28	1,30	16,88	9,66	1,54	-0,46	9,19	9,95	168,0	226,3
Wash water circulation pump + motor	P-104S	SS316 (Machined)	22,80	22,80	0,95	0,75	21,94	803,2	596,2	16,28	1,30	16,88	9,66	1,54	-0,46	9,19	9,95	168,0	226,3
Stripper reflux pump + motor	P-105A	SS316 (Machined)	8,81	8,81	0,95	0,75	8,48	803,2	596,2	6,29	1,30	6,52	14,67	2,24	-0,35	14,31	15,28	99,7	134,3
Stripper reflux pump + motor	P-105S	SS316 (Machined)	8,81	8,81	0,95	0,75	8,48	803,2	596,2	6,29	1,30	6,52	14,67	2,24	-0,35	14,31	15,28	99,7	134,3
LP steam condensate pumps	P-121A	SS316 (Machined)	9,85	9,85	1,00	0,75	9,85	803,2	596,2	7,31	1,30	7,58	14,67	2,24	-0,35	14,31	15,28	115,8	156,0
LP steam condensate pumps	P-121S	SS316 (Machined)	9,85	9,85	1,00	0,75	9,85	803,2	596,2	7,31	1,30	7,58	14,67	2,24	-0,35	14,31	15,28	115,8	156,0
Cooling water circulation pump	P-401A	CS	70,00	70,00	0,95	0,75	67,36	803,2	596,2	50,00	1,00	67,36	6,94	0,96	-0,29	6,64	6,64	447,3	602,6
Cooling water circulation pump	P-401B	CS	70,00	70,00	0,95	0,75	67,36	803,2	596,2	50,00	1,00	67,36	6,94	0,96	-0,29	6,64	6,64	447,3	602,6
Cooling water circulation pump	P-401C	CS	70,00	70,00	0,95	0,75	67,36	803,2	596,2	50,00	1,00	67,36	6,94	0,96	-0,29	6,64	6,64	447,3	602,6
Cooling water circulation pump	P-401S	CS	70,00	70,00	0,95	0,75	67,36	803,2	596,2	50,00	1,00	67,36	6,94	0,96	-0,29	6,64	6,64	447,3	602,6
Cooling water dry-cooler	E-401	CS	4.300,00	4.300,00	0,95	0,80	4.127,12	803,2	596,2	3063,33	1,00	4127,12	2,75	0,23	-0,08	2,68	2,68	11.055,7	14.895,0
Natural gas fired steam boiler unit	X-101	CS	382,60	382,60	0,00	0,75	0,00	803,2	596,2	0,00	1,00	0,00	13,12	2,24	-1,90	11,22	11,22	0,0	0,0
Amine reclaimer unit	X-102	SS316 (welded)	335,00	335,00	0,95	0,75	322,36	803,2	596,2	239,27	1,75	184,20	3,72	-0,11	-1,19	2,52	3,19	587,2	791,1
Amine solvent supply system	X-103	SS304 (welded)	10,00	10,00	0,95	0,65	9,67	803,2	596,2	7,18	1,60	6,05	14,21	2,24	-0,81	13,40	15,34	92,7	124,9
Total equipment cost (TEC) & Total plant cost (TPC), k€		k€		**15.518,22**			**14.576,66**										**4,04**	**46.543,5**	**62.706,4**

Table 6.4.4. Total Installed Plant (TPC) cost HS3 Case B

7 CO_2 capture cost evaluations

7.1 Introduction

Now the Total Plant Costs (TPC) or Fixed Capital Investment (FIC) and the OPEX costs are defined for each of the scenarios, the CO_2 capture costs for each of the considered scenarios can be calculated.

The TPC or so-called CAPEX needs to be converted to an annualized cost to determine the yearly average capital costs for the CO_2 capture plant. For this the TPC is multiplied by the so-called capital recovery factor (CRF).

CRF converts the present value of series payments over a fixed amount of time. Thus, the formula for CRF is:

$$\mathrm{CRF} = \frac{Rate}{1-(1+Rate)^{-Life}}$$

Where:

Life = project operating lifetime, yr

Discount rate / cost of capital (%)

It has been agreed with the partners to consider a 25-year plant lifetime and an 8% discount rate for calculating the annualized capitol cost.

The total yearly plant cost (TAC) can then be calculated according to the following expression:

$$\mathrm{TAC}\left(\frac{€}{yr}\right) = \mathrm{Annualized\ CAPEX}\left(\frac{€}{yr}\right) + \mathrm{Annual\ VOC}\left(\frac{€}{yr}\right) + \mathrm{Annual\ FOC}\left(\frac{€}{yr}\right)$$

Where:

VOC = Variable OPEX cost

FOC = Fixed OPEX cost

Now the CO_2 capture cost can be calculated according to the following expression:

$$\mathrm{CO_2}\ capture\ cost\left(\frac{€}{tCO_2}\right) = \frac{\mathrm{TAC}\left(\frac{€}{yr}\right)}{\mathrm{Mass\ of\ annual\ CO2\ captured}\left(\frac{\mathrm{tCO_2}}{\mathrm{yr}}\right)}$$

It is assumed that the CO_2 capture plant will have a downtime of 14 days per year, resulting in 8424 operating hours per year.

7.2 CO_2 capture costs base case scenario

Table 7.2.1 provides a breakdown of the CO_2 capture cost calculations for the considered scenarios based on 2023 CAPEX & OPEX pricing data.

CO2 capture costs estimation sheet	Irving Oil Whitegate Refinery CO2 capture costs				
Capture scenario -->	MEA Case A	MEA Case B	HS3 Case A	HS3 Case B	
Fixed Capital cost (CAPEX)	**value**	**value**	**value**	**value**	**Unit**
Total Plant Cost (TPC) or Total Fixed Costs (FIC)	65,210,282.37	60,410,971.18	66,652,094.58	62,706,404.79	€
Initial amine solvent filling cost	146,880.00	132,192.00	3,870,900.00	3,453,516.00	€
Project lifetime	25	25	25	25	yr
Discount rate	8%	8%	8%	8%	%
Capital Recovery Factor (CRF)	0.09368	0.09368	0.09368	0.09368	--
Annualized Capital Cost (AAC)	**6,122,579.17**	**5,671,609.61**	**6,606,508.03**	**6,197,780.60**	€
Variable OPEX cost (VOC)	**value**	**value**	**value**	**value**	**Unit**
Total yearly electricity cost	3,877,874.32	3,486,669.33	3,375,966.15	3,226,108.69	€
Total yearly Natural gas cost	5,433,820.04	N.A.	2,464,254.69	N.A.	€
Total yearly LP steam cost	N.A.	5,493,121.92	N.A.	2,468,063.52	€
Total yearly demin water cost	35,085.96	35,085.96	30,073.68	30,073.68	€
Total yearly amine solvent cost	1,288,872.00	1,153,870.76	6,712,617.23	6,414,329.28	€
Total yearly Caustic soda cost	151,632.00	135,749.50	52,647.98	50,308.46	€
Total yearly act. carbon cost	53,071.20	47,512.33	39,803.40	38,034.66	€
Total yearly variable OPEX	**10,840,355.52**	**10,352,009.80**	**12,675,363.12**	**12,226,918.30**	€
Fixed OPEX cost (FOC)	**value**	**value**	**value**	**value**	**Unit**
Yearly maintenance cost	1,956,308.47	1,812,329.14	1,999,562.84	1,881,192.14	€
Yearly insurance cost	1,304,205.65	1,208,219.42	1,333,041.89	1,254,128.10	€
Yearly labor / supervision & overhead costs	472,500.00	472,500.00	472,500.00	472,500.00	€
					€
Total yearly fixed OPEX	**3,733,014.12**	**3,493,048.56**	**3,805,104.73**	**3,607,820.24**	€
CO2 captured	**value**	**value**	**value**	**value**	**Unit**
Hourly CO2 capture rate	31.41	28.12	29.48	28.17	MT/h
Yearly CO2 capture rate	264,597.84	236,882.88	248,339.52	237,304.08	MT/yr
Total yearly plant cost (TAC)	**20,695,948.81**	**19,516,667.96**	**23,086,975.88**	**22,032,519.14**	€
CO2 capture cost (ex working capital)	**78.22**	**82.39**	**92.97**	**92.85**	€/MT
Estimated initial working capital (10% of TPC)	6,535,716.24	6,054,316.32	7,052,299.46	6,615,992.08	€
Estimated initial working capital (15% of TPC)	**9,803,574.36**	**9,081,474.48**	**10,578,449.19**	**9,923,988.12**	€
Estimated initial working capital (20% of TPC)	13,071,432.47	12,108,632.64	14,104,598.92	13,231,984.16	€

Table 7.2.1: CO_2 capture costs for MEA and HS3 Case A & B based on 2023 CAPEX & OPEX pricing.

The first point to note looking at table 7.2.1. is the major difference in CO_2 capture costs between the MEA and HS3 solvent. The decrease in specific reboiler duty for the amine stripper for the HS3 solvent cases compared to MEA solvent cases (as indicated in table 2.2.1) is largely offset by the very high cost for the HS3 solvent. Also note that the strength of the HS3 solvent is 55wt% whereas the strength of the MEA solvent is only 30wt% which aggravates the difference, since the inventories for the MEA and HS3 mixed solvent as used don't differ that much. The solvent losses are 1.43 kg MEA/MT CO_2 captured and 0.53 kg HS3/MT CO_2 captured respectively. These figures are based on operational experience and experiments performed in Tiller CO_2 plant at SINTEF.

A sensitivity on the HS3 solvent price is done in section 7.3.

For the MEA cases the natural gas fired boiler case (Case A) would be in favour of the steam import case (Case B). For the HS3 solvent there is almost no difference between the 2 scenarios.

The carbon tax on the export steam production in the power plant by additional natural gas firing makes this scenario unattractive. This is pronounced for the MEA case where heat consumption is much higher than for the HS3 solvent.

7.3 Sensitivity analyses CO_2 capture costs

A sensitivity analyses on the TPC has been performed to see its effect on the CO_2 capture cost.

Table 7.3.1 shows the results for the CO_2 capture costs for a 25% higher and a 25% lower equipment prices as listed in section 4.11 and 4.12, since this is the expected accuracy range for the equipment prices. Based on these new equipment prices the EDF method determines the new TPC.

CO2 capture costs estimation sheet	Irving Oil Whitegate Refinery CO2 capture costs				
Capture scenario -->	MEA Case A	MEA Case B	HS3 Case A	HS3 Case B	
CO2 capture cost	value	value	value	value	Unit
Base case	78.22	82.39	92.97	92.85	€/MT
High Capex (+25%)	84.33	88.33	99.61	99.47	€/MT
Low Capex (-25%)	70.66	74.40	84.46	84.39	€/MT

Table 7.3.1: Sensitivity on equipment cost impact on overall CO_2 capture cost.

Cost scenarios for the HS3 solvent ranging from 10 to 20 times the price of MEA solvent is considered and the impact on the relative CO_2 capture costs for the MEA and HS3 solvent for Case A are shown in table 7.3.2 and table 7.3.3.

HS3 / MEA solvent price ratio	CCcost HS3 / MEA Case A
20	1.31
15 (basecase)	1.19
10	1.07
7.5	1.00

Table 7.3.2: Relative CO_2 capture cost between MEA and HS3 solvent

For the HS3 solvent to be economically competitive with the benchmark MEA solvent the price ratio between the solvents needs to drop to below ca. 7.5, meaning a HS3 solvent price of max. €25.5/kg.

The costs of the HS3 amine solvent components for the Tiller campaign were:

- Hydroxyethyl pyrrolidine – 950 NOK/kg (about 95 euro/kg)
- Aminopropanol – 500 NOK/kg (about 50 euro/kg)

Since the HS3 solvent consists of 15wt% Aminopropanol and 40wt% Hydroxyethyl pyrrolidine the solvent HS3 cost for the Tiller campaign is calculated at ca. €83/kg.

The considered base case cost for the HS3 solvent is taken as €51/kg. This price could be realistic if the amine components can be produced in large quantities.

CO2 capture costs estimation sheet	Irving Oil Whitegate Refinery CO2 capture costs				
Capture scenario -->	MEA Case A	MEA Case B	HS3 Case A	HS3 Case B	
CO2 capture cost	value	value	value	value	Unit
HS3 / MEA solvent price ratio 20	78,22	82,39	102,46	102,31	€/MT
HS3 / MEA solvent price ratio 15 (basecase)	78,22	82,39	92,97	92,85	€/MT
HS3 / MEA solvent price ratio 10	78,22	82,39	83,47	83,38	€/MT
HS3 / MEA solvent price ratio 7,5	78,22	82,39	78,72	78,65	€/MT

Table 7.3.3: Specific CO_2 capture at varying HS3 solvent cost

The following future Natural Gas (NG) whole-sale price scenarios are considered in the CO_2 capture cost sensitivity analyses:

Base case scenario: €40/MWh thermal
High price scenario: €55/MWh thermal
Low price scenario: €25/MWh thermal

The corresponding whole-sale power prices assuming a carbon price of €85/MT are then:

Base case scenario: €115.5/MWh
High price scenario: €143.8/MWh
Low price scenario: €87.2/MWh

The results from the NG/power sensitivity analyses for a carbon price of €85/MT are shown in table 7.3.4.

CO2 capture costs estimation sheet	Irving Oil Whitegate Refinery CO2 capture costs				
Capture scenario -->	MEA Case A	MEA Case B	HS3 Case A	HS3 Case B	
CO2 capture cost	value	value	value	value	Unit
Base case scenario (40€/MWh therm., €85/t CO2)	78.22	82.39	92.97	92.85	€/MT
High NG/Power cost (55€/MWh therm., €85/t CO2)	89.51	92.10	100.02	98.91	€/MT
Low NG/Power cost (25€/MWh therm., €85/t CO2)	66.93	72.68	85.91	86.78	€/MT

Table 7.3.4: Sensitivity on NG/Power price for the CO_2 capture cost for an €85/MT carbon price.

In addition, a sensitivity analysis is done on the carbon price, considering a future carbon price of €150/MT and €250/MT for the base case NG/power price.

A carbon price of €250/MT is considered by the International Energy Agency (IEA) for the year 2050 where net zero emissions is forecasted to be reached.

These results of this analyses are shown in respective tables 7.3.5

CO2 capture costs estimation sheet	Irving Oil Whitegate Refinery CO2 capture costs				
Capture scenario -->	MEA Case A	MEA Case B	HS3 Case A	HS3 Case B	
CO2 capture cost	**value**	**value**	**value**	**value**	**Unit**
Base case scenario (40€/MWh therm., €85/t CO2)	78.22	82.39	92.97	92.85	€/MT
40€/MWh therm., €150/t CO2)	81.33	90.80	95.85	98.10	€/MT
40€/MWh therm., €250/t CO2)	86.11	103.75	100.29	106.19	€/MT

Table 7.3.5: Sensitivity on carbon price for CO_2 capture cost.

7.4 Reduced OPEX by use of advanced process control (NMPC)

The reboiler duty is a major contributor to the OPEX of the CO_2 capture plant, due to its heavy energy consumption. It is therefore of interest to reduce, and ideally to minimize, the *specific* reboiler duty (SRD), which is a quantification of the energy used per unit of CO_2 captured. The SRD, sometimes referred to as the energy efficiency number, is typically denoted in MJ/kg or GJ/ton CO_2 captured. While there are countless ways to operate a CO_2 capture plant for a given CO_2 capture ratio and flue gas, the *optimal* operating point which achieves the minimum SRD is *unique*. This is illustrated in Figure 7.4.1, where the SRD for a capture plant (more specifically, it is Technology Centre Mongstad TCM with flue gas from the natural gas combined cycle (NGCC) plant) is plotted as a function of the amine circulation rate while maintaining 90% capture ratio. If any of the operating conditions change, this picture changes and the optimal point moves.

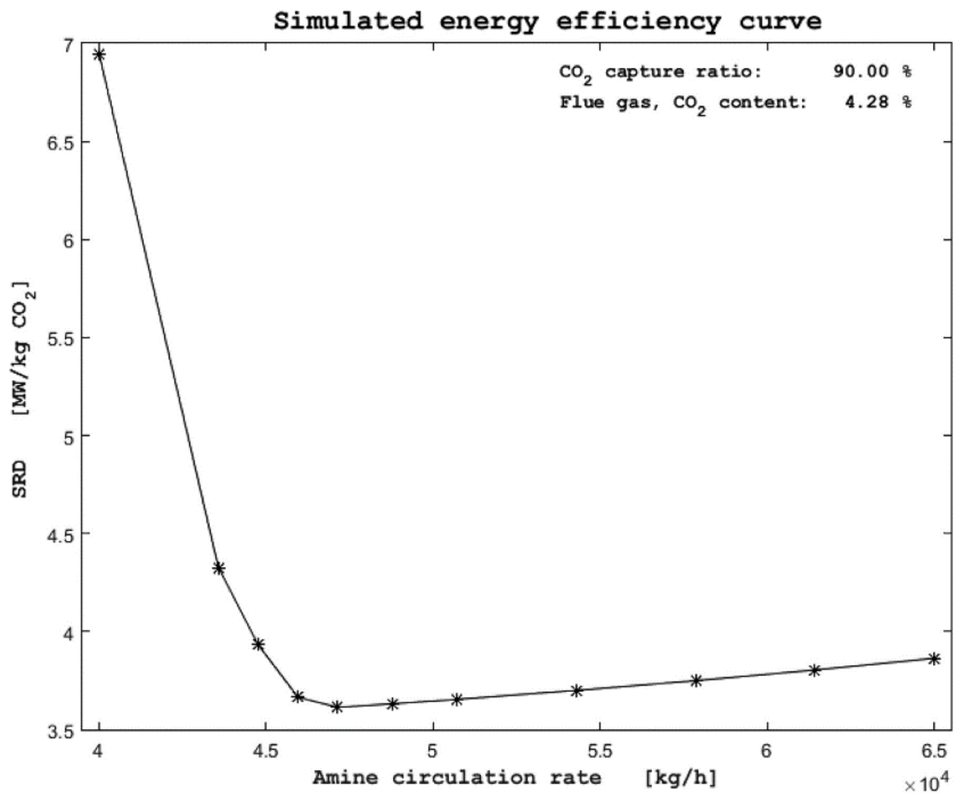


Figure 7.4.1. Specific reboiler duty (SRD) curve. Simulated example using the monoethanolamine (MEA) solvent to achieve 90% capture ratio for a typical NGCC exhaust at a scale comparable to Technology Centre Mongstad (TCM) according to Hauger et. al. (2019).

Finding the optimal operating conditions and maintaining optimality over time, e.g., when encountering disturbances or changes in operational demands, is crucial for maintaining low OPEX.

It is observed (Hauger et. al., 2019) that an experienced plant operator could perturb the capture plant towards the optimal point and even get close to it, but this is a tedious and *very* time-consuming micro-managerial task which binds up operator resources. Moreover, this effort will be in vain, should the operating conditions change, and the risk of moving the plant in the wrong direction is always present.

An alternative to a manually oriented control scheme is to achieve optimal operation using NMPC, having the reboiler duty and solvent recirculation rate as manipulated variables while controlling the capture ratio and minimizing the reboiler duty.

Basis for calculation of cost savings

The following considerations regarding cost savings are based on the utility prices that were introduced in Section 5.2, specifically the prices of Table 5.2.1. This table lists electrical power at 115.5€/MWh while steam is available at 57 €/MWh. It is assumed that the reboiler is steam-heated, here, but electrical power is included for the purpose of comparison. The potential cost savings, to be presented, scales linearly with these utility prices. Given the uncertainty in these utility prices, as discussed in Section 5, it must be emphasized that the indications regarding savings can change with time, and certainly change with local restrictions and policies, depending on the geographical location of the capture plant.

The cases that are mentioned here (more details in Table 2.2.1), for the purpose of illustrating the savings, which will also be comparably representative for their respective B-cases, are:

- MEA Case A: Capturing 31.41 tons of CO_2 per hour, with a reboiler duty of 33.05 MW.
- HS3 Case A: Capturing 29.48 tons of CO_2 per hour, with a reboiler duty of 24.45 MW.

For the calculation of pay-back time for such an advanced controller, an installation cost of 200k€ is set as the basis for a turn-key software system for advanced control, keeping in mind that this number can be higher or lower based on the case-specific details. For HS3 on the REALISE pilot, for instance, it is anticipated this number would be lower since the system is already developed and tested extensively.

Improved control of the capture process, including minimisation of energy usage

Cybernetica has demonstrated the use of NMPC for controlling CO_2 capture plants, both at the Tiller plant (SINTEF) and at TCM. The possible benefits of NMPC have been explored through various plant configurations and operating scenarios. The use of NMPC during varying operating conditions was demonstrated in REALISE using the HS-3 solvent, as reported in D2.4. Similar demonstrations were performed using the CESAR1 solvent at Tiller as part of the ALIGN-CCUS project, as described by Mejdell et. al. (2022), and at TCM as part of the DOCPCC-II project, as described by Hauger et. al. (2019), using the MEA solvent. In all projects, the NMPC was able to control the capture ratio and reject disturbances while minimizing the reboiler duty.

The benefits of NMPC have been previously demonstrated during the deliverables and milestones of WP2 and WP3, and it has been observed that NMPC offers superior control of the CO_2 capture plant towards its energy minimum, particularly in the presence of changing conditions and disturbances, compared to PI(D)-controllers. In contrast to conventional control approaches (i.e., PI(D) control, which requires accounting for several operating regions beforehand, as elaborated by Panahi & Skogestad (2011, 2012)), NMPC can use a single control configuration to handle a wide variety of operating conditions.

To achieve cost savings, the controller must *hit* the optimal point accurately (and not miss “on the left side” of the so-called U-curve, *cf.* Figure 7.4.1), and it must do so *quickly*. The estimated savings potentials are found by evaluating the ability of the NMPC to this, compared to a conventional approach. The SRD-curve will be solvent-dependent and depend strongly on the degree of heat integration in the plant, and the shape of this curve (whether it looks like a U or more like an L) will set the difficulty of finding (somewhere near) the optimal point "manually". Two scenarios are proposed:

- "Optimistic": 0.3 GJ/ton savings, on average
- "Conservative": 0.1 GJ/ton savings, on average

The level of variation in the flue gas (and other operating conditions) in the plant will affect the potential for cost savings, where a (hypothetical) *very* stable plant will point in the conservative direction while a plant with frequent disturbances will point in optimistic direction. Moreover, using HS3 would point in the conservative direction since the baseline reboiler duty is lower, compared to MEA. The assessment of possible cost savings is shown in Table 7.4.1, for the various cases and scenarios.

Case	Scenario	Savings [MW]	Reboiler	Savings [k€/day]	Pay-back time [weeks]
MEA	Optimistic (0.3 GJ/ton)	2.62	Steam	3.58	8.0
			Electrical	7.26	3.9
	Conservative (0.1 GJ/ton)	0.87	Steam	1.19	23.9
			Electrical	2.42	11.8
HS3	Optimistic (0.3 GJ/ton)	2.46	Steam	3.36	8.5
			Electrical	6.81	4.2
	Conservative (0.1 GJ/ton)	0.82	Steam	1.12	25.5
			Electrical	2.27	12.6

Table 7.4.1. Possible cost savings with advanced model-based process control to locate optimal operating point more accurately, faster.

Real-time optimization of energy usage, for varying price/availability of energy

The next step would be to exploit variations in energy costs or availability. The motivation for this investigation is the observed changes in available power from grid (e.g., due to introduction of intermittent energy production) and the resulting pricing trends. It is also interesting to address plants where excess heat can be integrated into CO_2 capture, and the availability of said excess heat can be strongly varying, depending on upstream processes.

A controller which optimizes the thermodynamic plant performance as well as cost of electricity has been developed and tested, as described by Kvamsdal et. al. (2018). The controller consists of a two-level hierarchy, with an NMPC and a dynamic real time optimizer (DRTO). The NMPC is the lower-level controller which controls the plant, by governing (some of) the base-layer controllers of the plant, while the DRTO is the upper-level controller ("supervisor") which performs repetitive dynamic optimization and gives instructions to the NMPC. The DRTO has knowledge about future energy prices and accumulated CO_2 capture rates for a specified time window. Based on these quantities, it generates a target CO_2 capture ratio trajectory for the NMPC to track. In the tests, the objective of the DRTO was to maintain an overall capture rate of 85% over 24 hours and to minimize the total energy cost. The NMPC has a shorter prediction horizon, typically between 3 and 5 hours. For the live tests, an energy price regime was suggested, where the energy price was assumed to follow a cosine function with a period of twelve hours and a range from NOK 0.0/kWh to NOK 0.5/kWh (0.05€/kWh). With these variations in energy price, the achieved energy cost savings were 8.3% compared to running the plant at steady state for the 24 hours. This proposed price regime is, notably, modestly representable for the electrical price in Norway at the time of the experiment. Given recent trends in the European power market, hereunder electrical power, as discussed in Section 5, it is plausible to see power prices with larger variations than this, and this will open for even larger savings by introducing flexible operation. With variations in steam availability and cost, a similar picture can be drawn. Based on the demonstrated results for 8.3% reduction, two scenarios are made:

- "Optimistic": 10% reduction
- "Conservative": 6% reduction

The assessment of possible cost savings is shown in Table 7.4.2, for the various cases and scenarios.

Case	Scenario	Savings [MW]	Reboiler	Savings [k€/day]	Pay-back time [weeks]
MEA	Optimistic (10% red.)	3.31	Steam	4.52	6.3
			Electrical	9.16	3.1
	Conservative (6% red.)	1.98	Steam	2.71	10.5
			Electrical	5.50	5.2
HS3	Optimistic (10% red.)	2.44	Steam	3.35	8.5
			Electrical	6.78	4.2
	Conservative (6% red.)	1.47	Steam	2.00	14.2
			Electrical	4.07	7.0

Table 7.4.2. Possible cost savings with flexible operation, using real-time optimisation where varying availability or prices of energy is exploited.

Energy optimization for varying price/availability of energy, using intermittent storage

The flexible plant operation offered by the two-level controller described above can be further expanded by using storage tanks for both rich and lean amine. These tanks are used for intermittent storage of solvent and allow for energy price dependent solvent regeneration. This will expand the optimization problem in the DRTO. A possible benefit of this configuration is that it allows for more consistent lean loading entering the top of the absorber column, which means the capture rate does not need to vary as much. It also allows for larger variations in solvent regeneration depending on the energy price without sacrificing the capture ratio. Essentially, it means shifting the flexible operation from the absorber-side of the plant to the desorber-side, as compared to the previous approach with flexible operation.

A possible downside with this approach is the fact that the stored solvent, particularly the rich solvent, is warmer than the ambient temperature which means that energy will be lost when storing it. Additionally, this approach requires extra investment cost for equipment associated with the storage tanks, and it is emphasized that the pay-back times that are indicated in Table 7.4.3 are based on the reduction in energy usage only.

The use of large storage tanks for energy optimization was demonstrated at the Tiller pilot plant, where large variation in stripper usage was demonstrated without modification to the existing plant beyond installation of two separate storage tanks for intermediate solvent storage. Using the same proposed variations for energy price as was used in the previous case, the energy cost reduction was between 25% and 30%. Given the considerations about availability and pricing of energy, from Section 5, two scenarios regarding price variations are made based on the results:

- “Optimistic”: 30% reduction
- “Conservative”: 25% reduction

The assessment of possible cost savings is shown in Table 7.4.3, for the various cases and scenarios.

Case	Scenario	Savings [MW]	Reboiler	Savings [k€/day]	Pay-back time [*days*]
MEA	Optimistic (30% red.)	9.92	Steam	13.4	14.6
			Electrical	27.5	7.3
	Conservative (25% red.)	8.26	Steam	11.3	17.7
			Electrical	22.9	8.7
HS3	Optimistic (30% red.)	7.34	Steam	10.0	19.9
			Electrical	20.3	9.8
	Conservative (25% red.)	6.11	Steam	8.4	23.9
			Electrical	16.9	11.8

Table 7.4.3. Possible cost savings with flexible operation, using intermittent solvent storage to exploit varying energy prices. Pay-back time considers only the price for software not increased cost of equipment e.g. due to high desorbing demand during low steam price periods.

7.5 Use of plastic materials

Plastic materials have proven to be an attractive alternative to traditional materials such as steel and concrete due to good performance and high corrosion resistance. Lower price has often been a major advantage but is not necessarily the case.

Still these materials can increase durability and have lower maintenance costs, which again will influence OPEX.

In this project different materials were tested to find out how the actual solvent influenced the material properties over time. Selection of materials was based upon Biobe AS experience and R&D activities with materials that showed promising results for use on Amino based CC plants.

For the REALISE project we focused on two main types of thermoplastics, PP and PPO.

For the CCUS industry plastics can be used in many areas. In this project, we have focused on the following product areas. The prices for the packings and demister in metal are based on extraction from vendor quote of price of complete package of internals for each column.

In table 7.5.1, table 7.5.2 and table 7.5.3 comparison between use of plastics and metal is shown.

Product Area	Capex Without composites € pr m height	Capex using composites € pr m height	Capex Savings €m	Capex Savings as a percentage %
Vessel, absorber and desorber	32.857	110.000	None	
Commentary: This project has shown that composites material can be used with good results. Meanwhile larger structures will be more expensive than counterparts in steel. The difference can be in the area of 2 to 4 times more expensive which initially will disqualify composite solutions.				

Table 7.5.1. Use of plastics as material of construction for vessels.

Product Area	Capex Without thermoplastic € pr m3	Capex Using thermoplastic. € pr m3	Capex) Savings € pr m3	Capex Savings as a percentage %
Structured Packings	1100	280	820	74,5
Random Packings	1300	220	1080	83,1
Commentary: Structured and Random packings in PP or PPO will cost less than counterparts in stainless steel. Performance based on flow and capacity is similar or sometimes even better than stainless steel versions. This is due to better design freedom to makes holes, surfaces more optimal for the solvent flow. Packings in PP and PPO can also be made more compact due to a different manufacturing method. The effect will be savings on volume (less space). In addition, comes 3x lighter weight which again can give reduced cost for internals like support plates and level dividers.				

Table 7.5.2. Use of plastics as material of construction for packing.

Product Area	Capex Without thermoplastic and composites €m2	Capex Using thermoplastic and composites €m2	Capex Savings €m2	Capex Savings as a percentage %
Demister	150	25	125	83
Commentary: Demisters made from PP or PPO will cost less than counterparts in stainless steel.				

Table 7.5.3. Use of plastics as material of construction for demisters.

One should note that the high temperature performance of thermoplastics and composite materials can be a limiting factor. There are alternative and more high temperature resistant options, but they come with a higher price. High-temperature composite materials and lightweight composites and can withstand up to 1000°C. Ceramic matrix composites, polymer matrix composites, metal carbides and nitrides are some of the major types of high-temperature composite materials used among end-users. Medium range temperature performance composites (up to approx. 300 C) while high range temperature performance composites (up to approx. 900 C).

The project has shown that larger units like tanks, strippers and absorbers will be more expensive in composite materials as long as we compare the same design. These materials cannot therefore be seen as a more economic option. In addition, there will be limitations in material performance.

For smaller products like packings and demisters, products in thermoplastics will offer lower prices and, in some respects, also better performance. Still alternatives in steel are better documented and established in the market.

Other products like fluid distribution systems, piping's and so on has not been evaluated in this project.

8 Conclusions

The Techno-Economical Assessment (TEA) as part of WP3. is performed based on the work completed in D 3.2 where four (4) scenarios for CO_2 capture from the Irving Oil Whitegate refinery were defined for benchmark solvent MEA and the newly developed amine solvent HS3. The yearly amount of CO_2 captured in the scenarios range from 0.275 to 0.25 million MT per year.

The main and most important conclusion from this assessment is that the benchmark MEA solvent is more economic than the HS3 solvent despite the ca. 20% lower specific energy consumption for the CO_2 capture process for this new solvent.

For the base case assumption that the HS3 solvent is 15 times more expense than the benchmark MEA solvent, the CO_2 capture cost for the HS3 solvent is estimated to be ca. 13-19% higher than for the MEA solvent depending on the external heat supply scenario.

For the advanced HS3 solvent to be become economically competitive with MEA solvent, the cost of the solvent needs to be reduced to below 7.5 times the cost of 30wt% MEA solvent for Case A and below 10 for Case B scenario.

For high natural gas and/or high carbon prices the difference will be less as can be seen from tables 7.3.3. and 7.3.4.

The scenario with the natural gas fired boilers to supply the remaining heat for the MEA solvent regeneration appears to be more economical attractive than the steam import scenario, mainly due to carbon taxation i.e. natural gas burning inside the refinery not being taxed or penalized due to 90% CO_2 capture from that flue gas where steam import will be taxed because no CO_2 capture is considered for the export steam generation from the nearby power plant. The export steam is considered to be produced by the CCGT power plant flue gas duct burners fired by natural gas

The use of plastic material results in lower capex when applied to the packing material for the towers but not when applied to the columns themselves.

Using NMPC is considered to give a considerable OPEX saving both when used to optimize current state of the capture plant and when used to distribute the rate of capture according to the predicted energy prices during a 24-hour period.

9 References

S.A. Aromada, N.H. Eldrup, L.E. Øi (2021). Capital cost estimation of CO_2 capture plant using Enhanced Detailed Factor (EDF) method: Installation factors and plant construction characteristic factors. International Journal of Greenhouse Gas Control 110 (2021) 103394.

A.M. Gerrard (2000). Guide to capital cost estimation, 4th edition, IChem.

DACE Price booklet, edition 36, June 2023

AACE International, Recommended practice No. 18R-97, COST ESTIMATE CLASSIFICATION SYSTEM – AS APPLIED IN
ENGINEERING, PROCUREMENT, AND CONSTRUCTION FOR
THE PROCESS INDUSTRIES
TCM Framework: 7.3 – Cost Estimating and Budgeting

Hauger et. al. (2019). Demonstration of non-linear model predictive control of post-combustion CO_2 capture processes. Computers and Chemical Engineering 123, pp. 184-195.

Kvamsdal et. al. (2018). Demonstration of two-level nonlinear model predictive control of CO_2 capture plants. 14th International Conference on Greenhouse Gas Control Technologies, GHGT-14, 21st – 25th October 2018, Melbourne, Australia.

Mejdell et. al. (2022). Demonstration of non-linear model predictive control for optimal flexible operation of a CO_2 capture plant. International Journal of Greenhouse Gas Control 117 103645.

Panahi & Skogestad (2011 & 2012). Economically efficient operation of CO_2 capturing process.

- Part I: Self-optimizing procedure for selecting the best controlled variables (2011), Chemical Engineering and Processing, Vol. 50, pp. 247-253
- Part II: Design of control layer (2012), Chemical Engineering and Processing, Vol. 52, pp. 112-124

RaboResearch, 2022, publication on the basics of electricity price formation.

IEA, (2021), Net Zero by 2050, A roadmap for the Global Energy Sector

10 Appendix 1

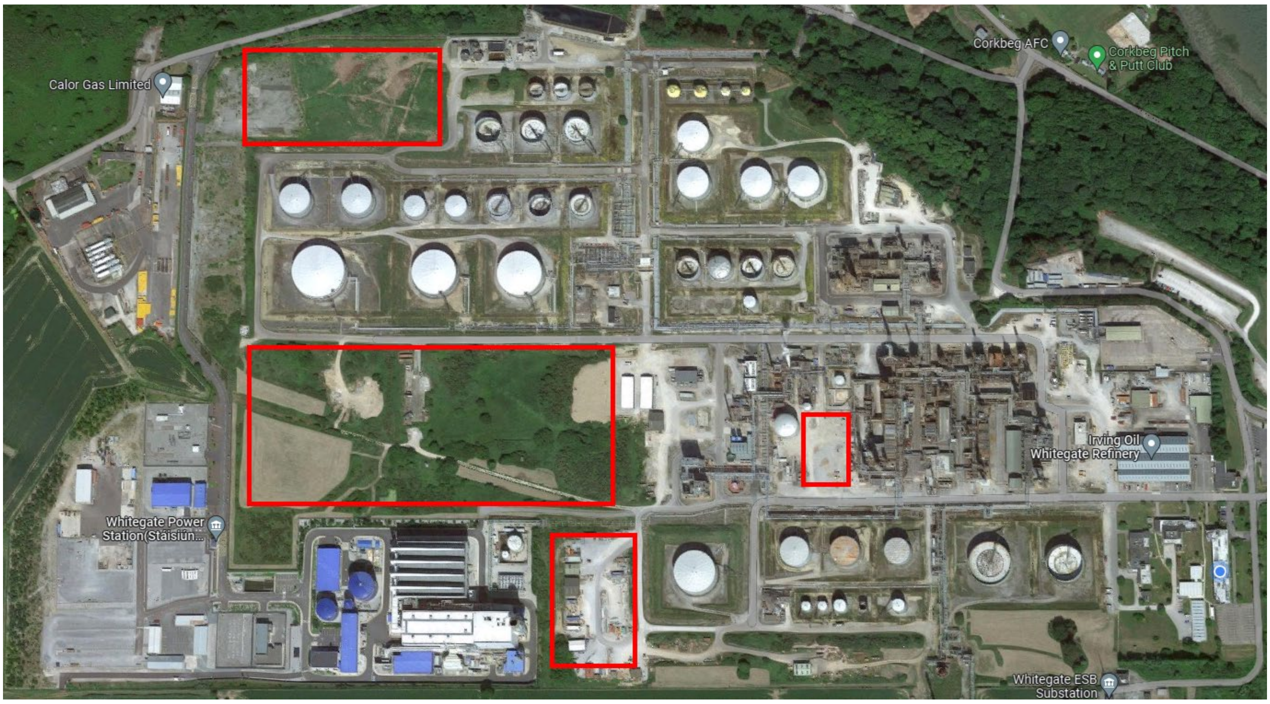


Fig. 10.1.1: Possible locations of CO_2 Capture Plant at Irving Oil Whitegate Refinery

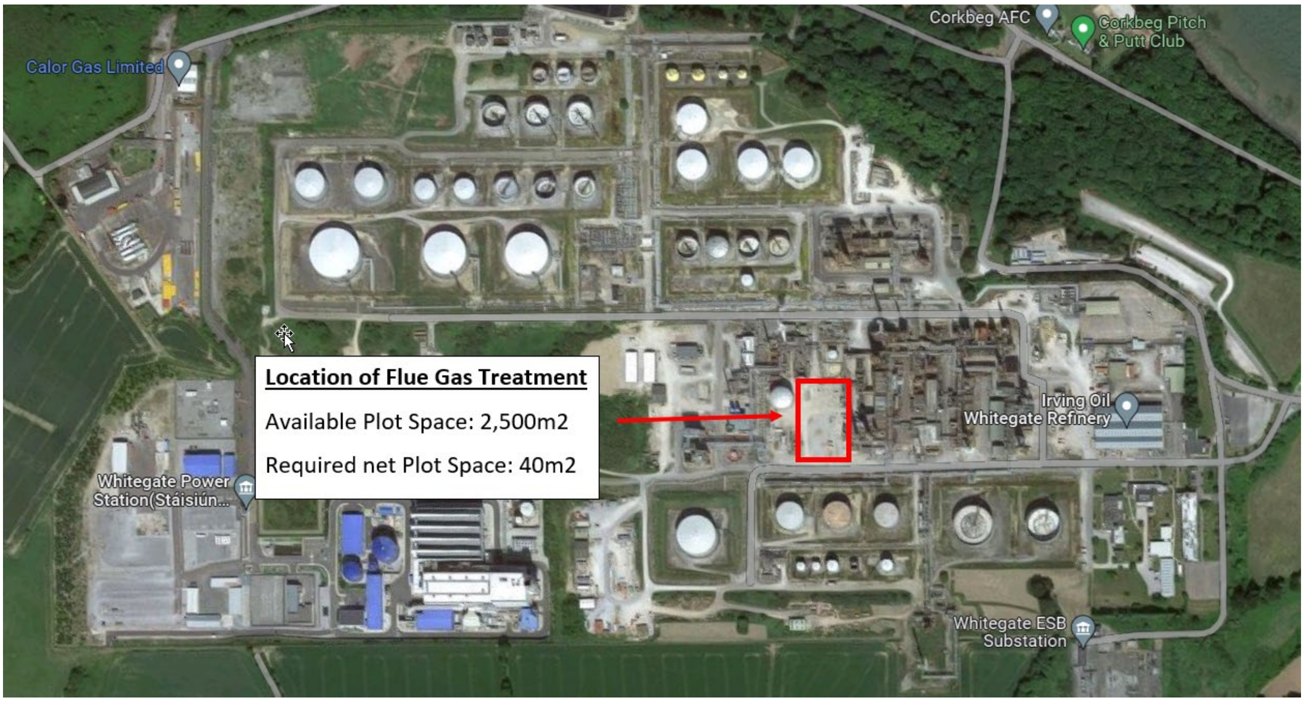


Fig. 10.1.2: Location of Flue gas treatment

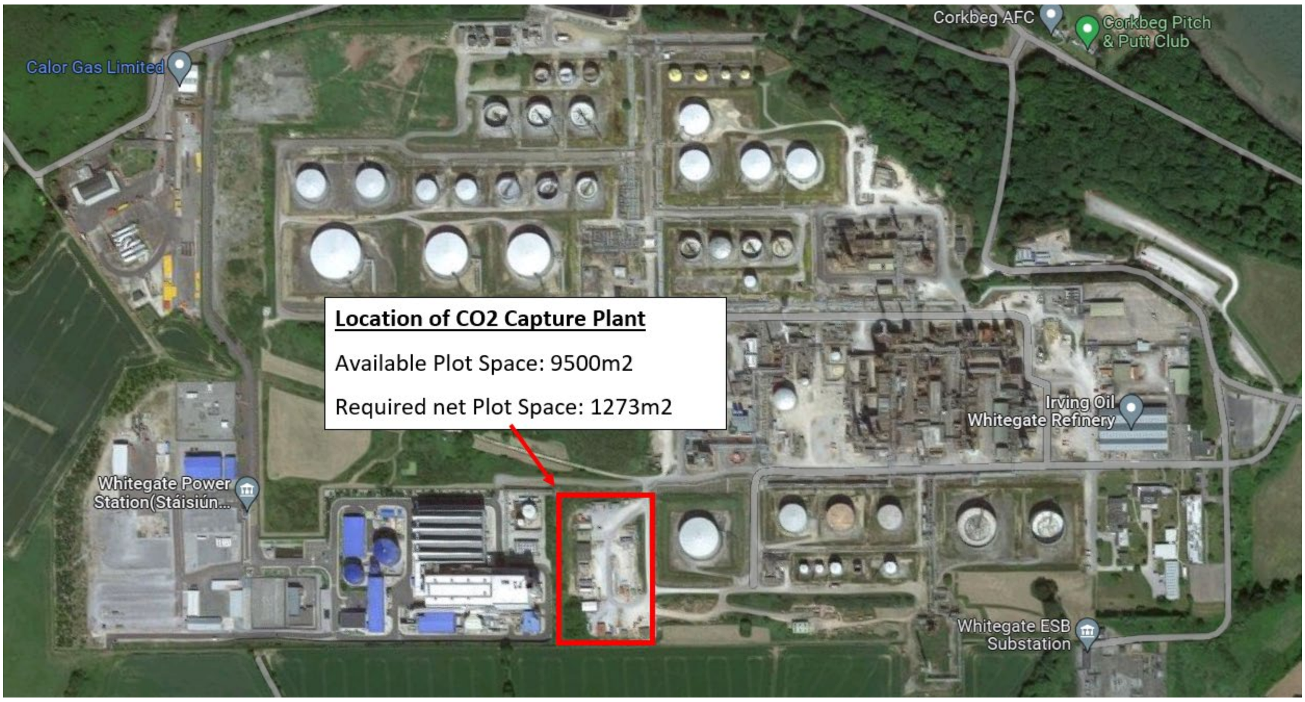


Fig. 10.1.3: Location of CO_2 Capture Plant