Simulation and Cost Estimation of CO_2 Capture with Alternatives for Doubled Capacity

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Abstract: This study presents a techno-economic assessment of an amine-based carbon capture technology. The aim is to compare different methods to evaluate the cost effect of doubling the capacity. A base case was established in Aspen HYSYS with 15 m absorber packing height, 6 m desorber packing height, removal efficiency of 85 % and a heat exchanger minimum temperature approach (ΔTmin) of 10 °C. In a first additional case the flue gas flow rate was doubled and in the second case a new absorber in parallel was added. Then dimensioning and cost estimation was carried out using Aspen HYSYS spreadsheets to automatically calculate CAPEX, OPEX and carbon capture cost per ton CO_2 captured. To estimate the Bare Erected Cost (BEC), the Enhanced Detailed Factor (EDF) and the Aspen Process Economic Analyzer (APEA) were employed. The EDF method determines the installation cost of each piece of equipment, while the Nazir-Amini method only offers the Total Plant Cost (TPC) without calculating individual equipment. Applying the EDF method, the TPC for the base case, the doubled feed gas case and the two-absorber case were calculated to 76, 141 and 150 MEuro respectively. This illustrates that cost increase may be less than proportional to the flow rate increase. The estimated annual OPEX for the base case was 42.5 MEuro, while for the two alternatives the OPEX was very close to the double of the base case. The estimated carbon capture cost for the base case, two-absorber case, and double feed gas scenario were 52.4 €/ton, 51.8 €/ton, and 50.5 €/ton, respectively. The study demonstrates that a combination of Aspen HYSYS simulation, Aspen Process Economic Analyzer and the EDF method is an effective method to evaluate different alternatives for increasing the capacity.

Keywords: *Carbon capture, Aspen HYSYS, simulation, dimensioning, cost estimation*.

1. INTRODUCTION

1.1. Aim

The first aim of this work is to compare different methods to cost estimate a CO_2 capture process based on process simulation. The second aim is to evaluate how efficient the different tools are to calculate different process alternatives and especially evaluate the cost effect of doubling the feed gas capacity of the CO_2 capture process.

1.2. Literature

There are several tools available to perform cost estimation of a process simulated in a process simulation tool like Aspen HYSYS or Aspen Plus. The Aspen Process Economic Analyzer APEA) is a tool that is a part of Aspen HYSYS and Aspen Plus. An alternative is factor based methods, like different detailed factor methods like the Enhanced Detailed Factor (EDF) method developed at USN (Ali, 2019; Aromada et al., 2021).

Much general work has been published on cost estimation of CO_2 capture plants (Rubin et al., 2013; van der Spek et al., 2019; Roussanaly et al., 2019), but in these methods the cost estimation is traditionally performed independent of a process simulation tool. Other publications presenting both process simulation and cost estimation are (Mores et al., 2012; Agbonghae et al., 2014; Manzolini et al., 2015; Luo and Wang, 2016; Eldrup et al., 2019 and Hasan et al., 2020). A traditional limitation for the efficiency of the cost estimation in these references, is that the cost estimation is performed for each case with added specifications for each specific case.

For CO_2 capture, a focus at USN has been on automatic process simulation combined with cost estimation in Aspen HYSYS (Øi et al., 2021; Øi et al., 2022; Shirdel et al., 2022). This work is based on the Master Thesis of Masoumeh Dehghanizadeh (2023). In this work, it is aimed to compare the accuracy and efficiency of different tools for combined simulation and cost estimation.

1.3. Process Description

Figure 1 illustrates a typical CO_2 absorption process using amine-based systems. The CO_2 rich gas is first cooled in a direct contact cooler (DCC) and the CO_2 is then absorbed into the monoethanol (MEA) solvent and removed from the gas stream in an absorber. The CO_2 rich solvent is then pre-heated and pumped into a desorber column, where it is heated and the CO_2 is stripped off the CO_2. The regenerated solvent is recycled to the absorber tower, while the high purity CO_2 stream off the top of the desorber column is sent further to processing for transportation and storage. If the flue gas capacity is doubled, another absorber can be set in parallel to the one in Fig. 1.

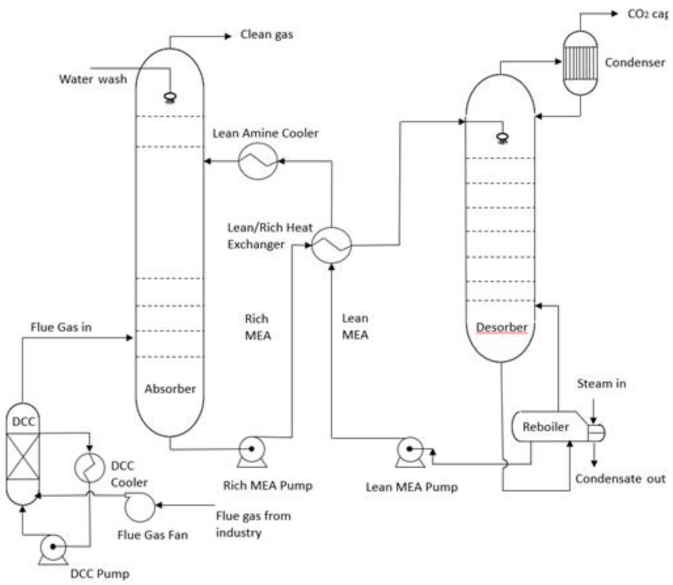

Fig. 1. Process flow diagram of a standard amine-based CO_2 capture process (Aromada et al., 2020).

2. SPECIFICATION AND SIMULATIONS

2.1. Specifications and simulation of base case CO_2 capture process

The Aspen HYSYS V12 was used to simulate an amine-based CO_2 capture process. The Acid Gas property package was employed, which includes the electrolyte non-random two-liquid (e-NRTL) model for electrolyte thermodynamics and the Peng-Robinson equation of state for the vapor phase.

The absorber and desorber were simulated using equilibrium stages with Murphree stage efficiencies. The Murphree efficiency is defined by dividing the change in CO_2 mole fraction from one stage to the next by the change on the assumption of equilibrium.

The specifications for the base case Aspen HYSYS simulation are given in Table 1. These specifications give a 85 per cent CO_2 removal efficiency and a minimum approach temperature of 10 °C in the lean/rich amine heat exchanger. The simulation is similar to earlier studies (Øi, 2007; Aromada et al., 2021 and Shirdel et al., 2022). The absorber has 15 stages with Murphree efficiency 0.15, while the desorber has 10 stages with Murphree efficiency 0.5. In the columns, the Modified HYSIM Inside-Out numerical solver was selected. The adiabatic efficiency of the pumps was specified to be 75%.

2.2. Calculation sequence

The calculation sequence in the Aspen HYSYS flowsheet in Figure 2 is similar to the simulations in Øi et al. (2022) and Shirdel et al. (2022). In the base case there is only one recycle block to check that the amine liquid flow recirculated is equal to the inlet flow to the absorption column. Figure 3 illustrates the process flow diagram of the two-absorber scenario with two simulated absorption columns.

Table 1: Specifications for the base case alternative

Parameter	***Value***
Inlet flue gas temperature [ºC]	*40.0*
Inlet flue gas pressure [kPa]	*110*
Inlet flue gas flow rate [kmol/h]	*85000*
CO_2 content in inlet gas [mole %]	*3.73*
Water content in inlet gas [mole %]	*6.71*
Lean amine temperature [ºC]	*40.0*
Lean amine pressure [kPa]	*110.0*
Lean amine rate [kg/h]	*103500*
MEA content in lean amine [mass %]	*29*
CO_2 content in lean amine [mass %]	*5.4*
Number of stages in absorber [-]	*15*
Murphree efficiency in absorber	*0.15*
Rich amine pump pressure [kPa]	*200.0*
Rich amine temp. out of HEX [ºC]	*104*
Number of stages in desorber [-]	*6*
Murphree efficiency in desorber	*1.0*
Reflux ratio in stripper [-]	*0.3*
Reboiler temperature [ºC]	*120.0*

2.3. Equipment dimensioning

The dimensioning of all the equipment (except for the DCC unit) were performed as in previous studies (Øi et al., 2022; Shirdel et al., 2022). The diameters of the absorption and desorption columns were evaluated from the gas volumetric flows and based on a superficial gas velocities of 2.5 m/s for the absorber and 1 m/s for the desorber column. Each packing stage in the absorber and desorber was assumed to be 1 m high. To include the height for packing, liquid distributors, water wash, demister, gas inflow, gas outflow and sump, the total column heights are considerably larger, and set to 30 m and 16 m for the tangent-to-tangent heights of the absorber and desorber column.

The overall heat transfer coefficients specified are 1.20 kW/(m²·K) for the reboiler, 0.73 kW/(m²·K) for the lean/rich heat exchanger, 0.80 kW/(m²·K) for the amine cooler, and 1.00 kW/(m²·K) for the condenser as in Aromada et al. (2022). The pumps had an efficiency of 0.75. It was assumed that the maximum heat exchanger size is 1000 m^2, and in case of the need for larger heat exchanger area, more units are necessary.

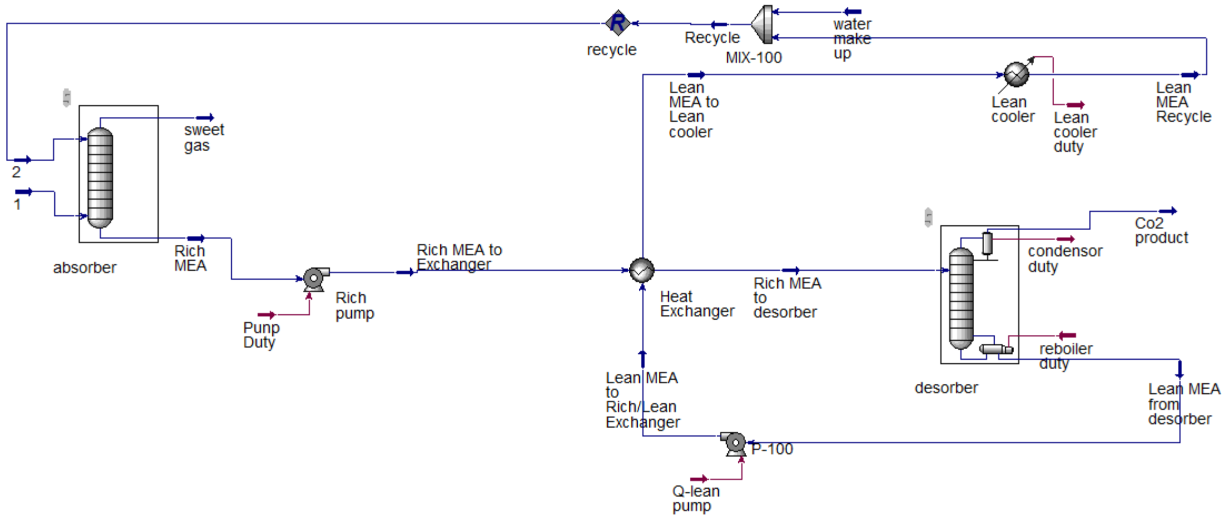

Fig. 2. Aspen HYSYS flowsheet for the base case (Dehghanizadeh, 2023)

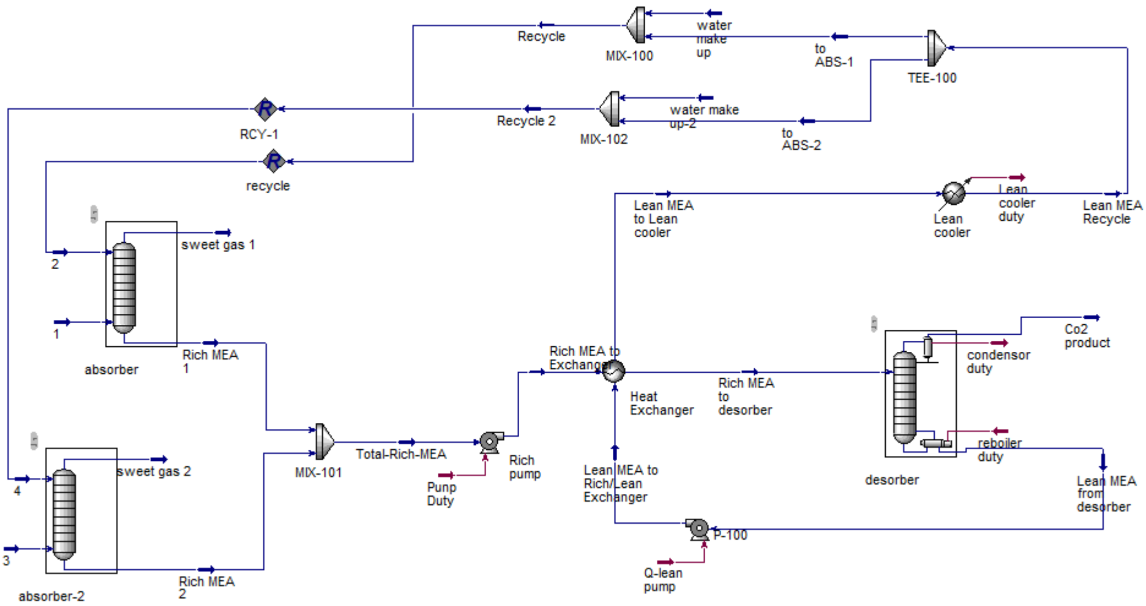

Fig. 3. Aspen HYSYS flowsheet for the case with two simulated absorption columns (Dehghanizadeh, 2023)

3. COST ESTIMATION PROCEDURES AND ASSUMPTIONS

3.1. Capital cost estimation method

The purchased cost of each equipment unit is estimated in this work with Aspen In-Plant Cost Estimator based on the dimensioning.

After estimating the cost of each part of equipment, cost factors are added to obtain the quantities Bare Erected Cost (BEC) and Total Plant Cost (TPC). A description of what is traditionally included in the BEC, and what is traditionally included in the TPC is presented and discussed in Rubin et al. (2013). The BEC and TPC are defined differently in different literature (Rubin et al, 2013). In this work the BEC is determined using the EDF method by creating a detailed list of all the process equipment, obtaining estimates on purchased equipment cost and estimating all the cost of material and labour required to complete the installation. It includes the cost of equipment, erection, piping, electro, instrument, ground work, steel and concrete, insulation and engineering. To obtain the TPC, contractor services, process contingency and project contingency is also included. Then the cost of the equipment is adjusted to the correct size, year, and material of construction. This method is documented in (Ali, 2019 and Aromada et al., 2021).

Another approach to estimate BEC employed in this study is the Aspen Process Economic Analyzer (APEA). It relies on model-based estimation to generate project cost estimates. The APEA can calculate not only the equipment cost but also the installed direct cost (piping, civil, structural steel, insulation, etc.) for each process equipment. The equipment cost calculated using APEA and Aspen In-Plant has in this work been compared, and the results were very similar.

To calculate the TPC, the Nazir-Amini method (Nazir et al., 2018) was used as an alternative to the EDF method. In this work 10 % of BEC is added for engineering procurement construction cost, 10 % for process contingency and 15 % for project contingency is added to obtain the TPC.

The cost currency and cost year were Euro (€) and 2019 for Aspen In-Plant and 2020 for the detailed factor table. The default location in Aspen In-Plant Cost Estimator, Rotterdam, was assumed in this work. The equipment units were assumed to be constructed from stainless steel SS316. The material factor for welded equipment was 1.75 and 1.30 for machined equipment.

The total installation cost factor includes the sub-factors for direct costs, engineering costs, administration costs, and commissioning and contingency costs. Equation (1) is used to calculate the total installation factor in carbon steel ($F_{T,CS}$). The procedure of utilizing the EDF method for TPC calculation corresponds to the methodology outlined in Ali (2019).

$$F_{T,CS} = f_{direct} + f_{eng} + f_{adm} + f_{comm} + f_{cont} \quad (1)$$

where the subscripts in the factors means direct installation cost, engineering, administration, commisioning and contingency. The individual factors are in this work from an EDF table sheet in (Aromada et al., 2021).

The total equipment installed cost (EIC) for each unit in carbon steel can be calculated from Equation (2).

$$EIC_{CS} = F_{T,CS} \times Equipment\ cost_{CS} \quad (2)$$

Total plant cost is the sum of the total installation costs for each equipment unit and is calculated by Equation (3). In the case of calculating BEC, the factors for administration, commisionong and contingency is ommited in Equation (1).

$$TPC\ (2019) = \sum EIC\ (all\ equipment) \quad (3)$$

If the equipment is to be made of a material other than carbon steel, the installation factor must be adjusted accordingly. Equation (4) is used to make this correction:

$$F_T = \left[F_{T,CS} + (f_{mat} - 1)\ x\ (1 + f_{T,pp,CS})\right] \quad (4)$$

where f_{mat} is the material factor which is the ratio between the unit cost and the unit cost in carbon steel, and $f_{pp,CS}$ is the piping factor (for carbon steel) in the EDF table sheet.

The capital cost of the CO_2 capture plant is then escalated from 2019 using a consumer cost index from Statistisk Sentralbyrå (SSB).

During optimization or sensitivity analysis, where a parameter is varied, the capacities/sizes of some equipment will change. Therefore, there is a need to estimate new cost for the equipment units due to the resulting changes in size/capacity. This is automatically estimated based on the Power law using an exponent of typically 0.65 based on the previous cost obtained from Aspen In-Plant Cost Estimator as done in (Aromada et al., 2022; Øi et al., 2022).

$$Cost_{NEW} = Cost_{OLD}\ x\ \left(\frac{Capacity_{NEW}}{Capacity_{OLD}}\right)^{0.65} \quad (5)$$

3.2. Operating cost estimation and assumptions

The annual operating cost in this work is the sum of the fixed operating cost and variable operating costs estimated as in Øi et al. (2022):

$$Annual\ cost = Consumption \times Unit\ cost \quad (6)$$

The assumptions used for estimating the annual operating cost are presented in Table 2. The values are similar to values used in earlier work like Aromada et al. (2021).

Table 2: Annual operating cost assumptions

Item	***Unit***	***Value***
Operating lifetime	*[Year]*	*22(2+20)*
Annual hours of operation	*[h/year]*	*8000*
Electricity cost	*[€/kWh]*	*0.132*
Steam cost	*[€/kWh]*	*0.032*
MEA cost	*[€/ton]*	*1450*
Maintenance cost	*[€/year]*	*4% of CAPEX*
Operator cost (6 oper)	*[€/year]*	*85350(*6)*
Engineer cost (1 eng)	*[€/year]*	*166400*

3.3. CO_2 capture annualized cost

An economic key performance indicator in this work is CO_2 captured cost. This was estimated using Equations (7) to (10), as shown in (Aromada et al., 2021):

$$CO_2\ captured\ cost = \frac{Total\ annual\ cost}{Mass\ of\ Captured\ CO_2/year} \quad (7)$$

$$Total\ annual\ cost = Annualized\ CAPEX + Yearly\ OPEX \quad (8)$$

$$Annualized\ CAPEX = \frac{CAPEX}{Annualized\ factor} \quad (9)$$

$$Annualized\ factor = \sum_{i=1}^{n} \left[\frac{1}{(1+r)^n}\right] \quad (10)$$

where n is the plant lifetime, 22 years which includes 2 years for the plant's construction. And r is the discount rate and was assumed to be 7.5 %.

4. RESULTS AND DISCUSSION

4.1. BEC and TPC for the base case

Figure 4 shows the Bare Erective Cost (BEC) calculated with the EDF method and the Aspen Economic Analyzer. The contribution from each equipment unit is also shown in the figure. It shows that the absorber is the dominating part, and then the main heat exchanger. It also shows that the EDF method and the results from the Aspen Economic Analyzer (APEA) give reasonable close results (within 5-10 %).

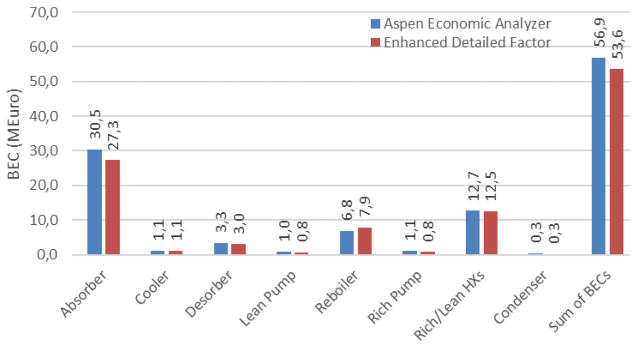

Fig. 4. BEC comparison for the Base Case applying the APEA and EDF method (Dehghanizadeh, 2023)

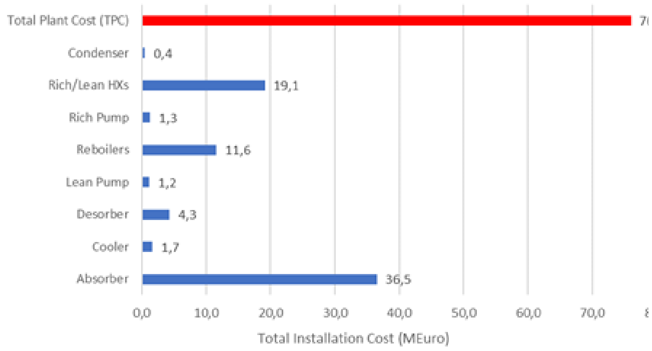

Fig. 5. Total installation cost (TPC) applying the EDF method (Dehghanizadeh, 2023)

Figures 5 and 6 show Total Project Cost (TPC) and OPEX for the base case. The values for the TPC are higher, but the cost distribution is similar to the BEC values. For OPEX, steam for heating is as expected the most significant part.

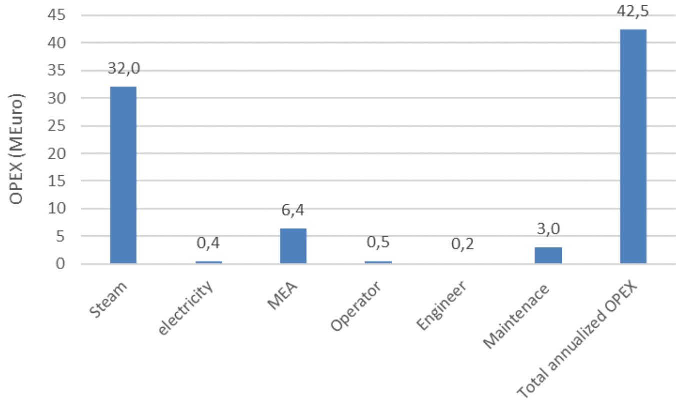

Fig. 6. OPEX estimated for the Base Case (Dehghanizadeh, 2023)

4.2. Results for doubled capacity

Figures 7 and 8 show a BEC comparison for the Base case and Doubled feed gas applying the EDF and APEA methods. It shows that the absorber cost and total cost increases a little less than to the double cost.

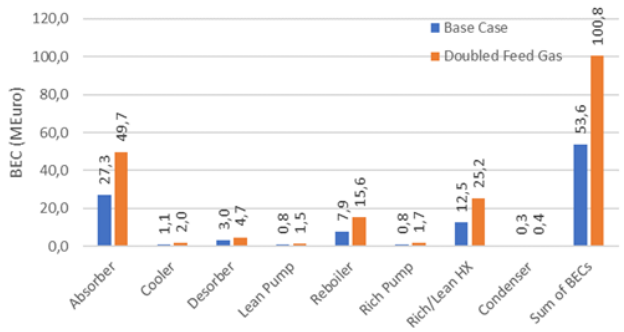

Fig. 7. BEC comparison for the Base case and Doubled feed gas applying the EDF method (Dehghanizadeh, 2023)

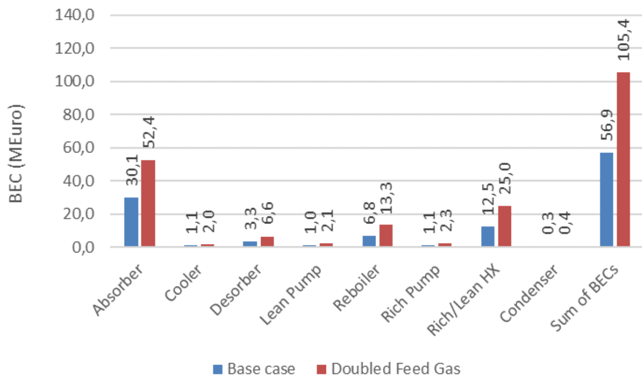

Fig. 8. BEC comparison for the Base case and Doubled feed gas case applying the APEA method (Dehghanizadeh, 2023)

Figure 9 is showing the TPC for the Doubled feed gas by the EDF method. It shows that the increase is lower than the double of the TPC for the base case, 140.4 compared to 76 MEuro.

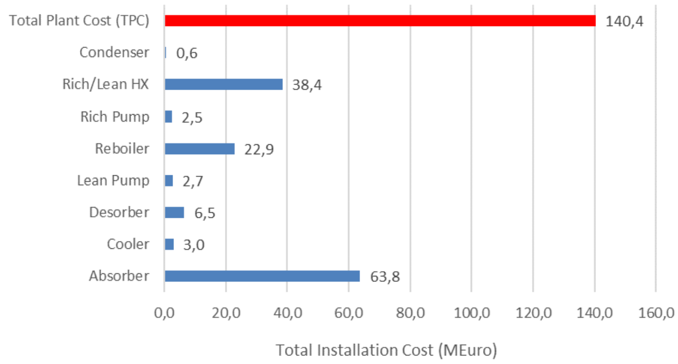

Fig. 9. TPC for Doubled feed gas using thed EDF method (Dehghanizadeh, 2023)

Figure 10 shows a comparison of TPC calculated by the EDF method, the Nazir-Amini method and use of the power law. It shows that the EDF method and Nazir-Amini method are close, while applying the power law is considerably lower. It is expected that the use of the EDF method is the most accurate because it is more detailed.

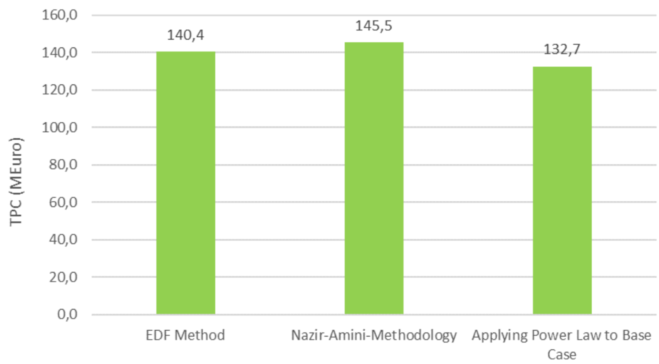

Fig. 10. TPC for Doubled Feed gas applying the EDF method (Dehghanizadeh, 2023)

4.3. Results for two-absorber scenario

Figures 11 and 12 show calculated BEC for the Doubled feed case and the Two-absorber case calculated by the EDF method (Fig. 11) and the APEA method (Fig. 12). Both methods show that the Two-Absorber case is slightly more costly.

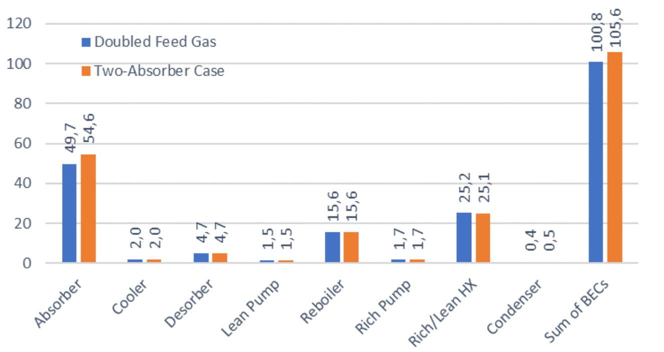

Fig. 11. Comparison of BEC for Doubled feed gas case and Two-absorber case applying the EDF method (Dehghanizadeh, 2023)

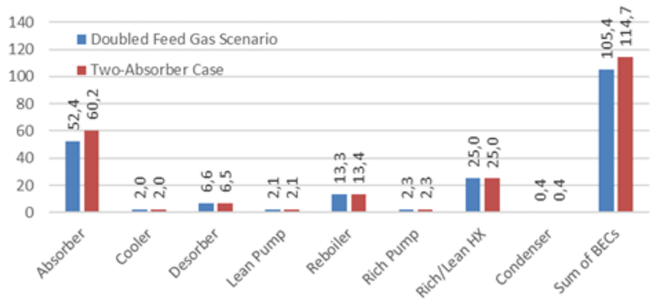

Fig. 12. Comparison of BEC for Doubled feed gas case and Two-absorber case applying the APEA method (Dehghanizadeh, 2023)

Figure 13 shows the TPC calculated for the Two-absorber case. Compared to the calculation for the Doubled feed case in Fig. 9, it is considerably more expensive (149.7 compared to 140.4).

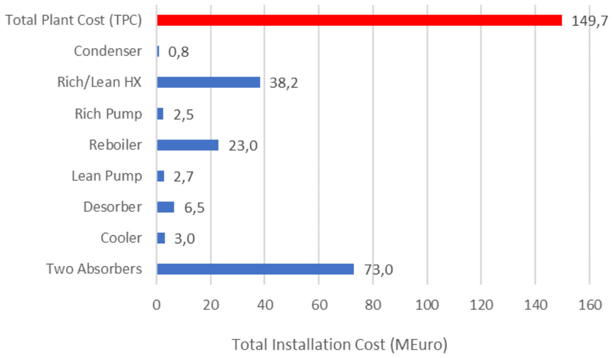

Fig. 13. TPC for Doubled feed gas applying the EDF method (Dehghanizadeh, 2023)

Figure 14 shows a comparison of TPC calculated by the EDF method, the Nazir-Amini method and use of the power law. It shows that the methods give close to the same results, but the Nazir-Amini method gives the highest value. It is expected that the EDF method is most accurate for sensitivity calculations of different parameters because it is more detailed. The Nazir-Amini additional factors are very general.

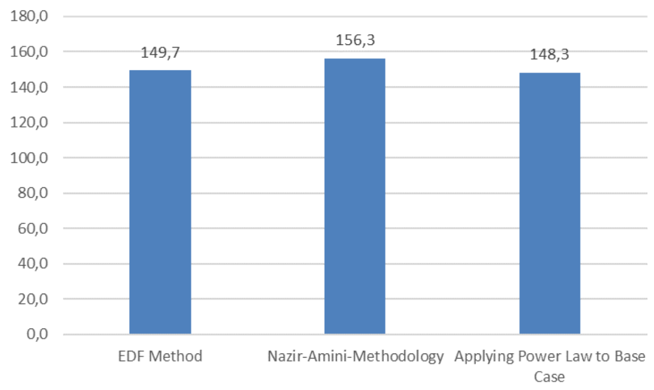

Fig. 14. TPC for Two-absorber case calculated by different methods (Dehghanizadeh, 2023)

Using the power law gives approximately the same result compared to the more detailed EDF method. The cost is as expected higher (about 8 %) than for the Doubled feed scenario.

Figure 15 shows the TPC as a function of gas flow, using the EDF method. The sensitivity calculation is performed automatically by using a Case study function in Aspen HYSYS. It shows that the cost is increasing a little less than proportional to the gas flow. This is as expected because the power law is used, which specifically calculates a cost for the absorber less than proportional to the gas flow. It shows that it is straightforward to use the EDF method using the power law for a fast and automatic sensitivity analysis.

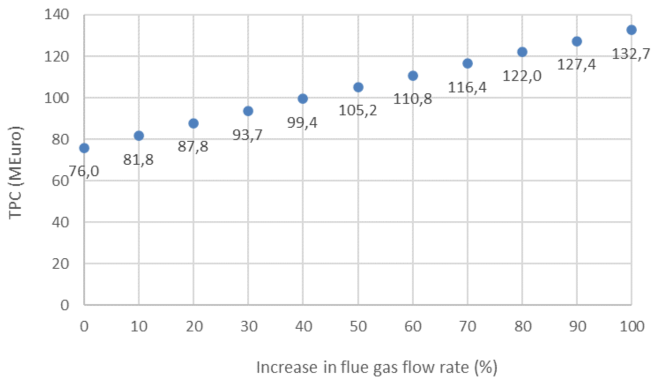

Fig. 15. Impact of flue gas increase on the TPC using the EDF method and the power law for equipment cost estimation at changed capacity (Dehghanizadeh, 2023)

4.4. Uncertainties in the cost estimation and cost comparison

The uncertainties in the absolute value of calculated CAPEX and OPEX for each case is large. An uncertainty for the CAPEX of +/- 50 % has been suggested (Ali, 2019). The uncertainty of the OPEX is even larger, especially due to the high uncertainty in heat and electricity cost (Aromada et al, 2021). However, in this work accurate absolute values of CAPEX and OPEX was not the main aim.

The main aim in this work was to make efficient cost comparisons of specific process alternatives using different tools. The results indicate that the results from the different calculation methods, especially the EDF and APEA methods, gave quite similar values. When comparing the process alternatives, the EDF and the APEA methods estimate similar cost differences between the double feed gas and two-absorber case. The higher cost of the two-absorber alternative is regarded to be significant, even though the absolute values of the cost estimates are inaccurate.

5. CONCLUSIONS

A base case was established in Aspen HYSYS with 15 m absorber packing height, 6 m desorber packing height, removal efficiency of 85 % and a heat exchanger minimum temperature approach (ΔTmin) of 10 °C. In a first additional case the flue gas flow rate was doubled and in the second case a new absorber in parallel was added. Then dimensioning and cost estimation was carried out using Aspen HYSYS spreadsheets to automatically calculate CAPEX and OPEX and carbon capture cost per ton CO_2 captured. To estimate the Bare Erected Cost (BEC), the Enhanced Detailed Factor (EDF) and the Aspen Process Economic Analyzer (APEA) were employed. The EDF method determines the installation cost of each piece of equipment, while the Nazir-Amini method only offers the TPC without calculating individual equipment. Applying the EDF method, the TPC (CAPEX) for the base case, the doubled feed gas case and the two-absorber case were calculated to 76, 141 and 150 MEuro respectively. This illustrates that the cost increase may be less than proportional to the flow rate increase. The estimated annual OPEX for the base case is about 42.5 MEuro, while for the two alternatives the OPEX was very close to the double of the base case. The estimated carbon capture costs for the base case, two-absorber case, and double feed gas scenario were 52.4 €/ton, 51.8 €/ton, and 50.5 €/ton, respectively. The study demonstrates that a combination of Aspen HYSYS simulation, Aspen Process Economic Analyzer and the EDF method is an effective method to evaluate different alternatives for increasing the capacity.

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