Pinch Analysis of 1,3-Butadiene and ETBE Plants at Sines Petrochemical Complex

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December 2016

Abstract

This paper describes a heat integration study carried out at 1,3-butadiene (BTD) and ETBE plants of Repsol Polímeros at Sines Petrochemical Complex. To identify the process areas where there is possibility to reuse the excess of enthalpy, the pinch technology was applied, for which was using the software Aspen Energy Analyzer. For this purpose, a simulation for both plants was performed using the simulation software Aspen Hysys. In this work several proposals for the retrofit of heat exchanger network (HEN) are presented, as well as for the reformulation of the utilities system. The final integration proposal suggests an energy integration of 9 836 MW/year, which corresponds to an annual saving of 989 k€. The projects included in this proposal need five new heat exchangers (HE) that account for a total investment of 328 k€. Therefore, it is estimated that the investment can be recovered in 4 months and 25 days.

Keywords: Heat Integration, Pinch Analysis, 1,3-Butadiene, ETBE, *Aspen Hysys*, *Aspen Energy Analyzer*

1. Introduction

Energy is an important topic in our day life. In petrochemical industry this is even more significant, due to the huge amounts consumed. The current global energy outlook [1] requires that companies follow a strategy focused on optimizing the efficiency of its industrial processes in order to remain competitive and sustainable.

This study aims to achieve energy integration solutions that allow Repsol Polímeros reuse the circulating energy in 1,3-Butadiene (BTD) and ETBE plants in order to ensure better energy performance and consequently lower operating costs associated with external energy consumption.

2. Pinch Technology

The Pinch Technology is one of the most used methods to identify the process areas where there is possibility to recycle the excess of enthalpy - [2-6]. The principle of this technology is to reuse the heat between process streams (PS), in order to reduce the external utilities consumption. The PS are defined as hot streams (HS) and cold streams (CS). The HS are streams that provide heat, since they need to be cooled down or go through a state transition. On the contrary, CS need to receive heat, due to the require to be heated up or suffer a state transition. In a process without heat integration these streams are cooled down or heated up indirectly with exterior fluids defined as

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cold utilities (CU) and hot utilities (HU), respectively.

The pinch concept represents the temperature for which there is a minimum difference between the temperature of CS and HS (ΔT_{min}). For petrochemical and chemical industries, it is suggested the use of a ΔT_{min} between 10 and 20ºC. [3]

The pinch separates the system in two different zones: the zone above the pinch and the zone below the pinch. The zone above is called the heat source and the HS are cooled with CS, in case of extra need for heat HU can be used. The zone below is named the heat sink and the CS are heated with HS, in the case of heat excess it can be used CU. As such, there are three basic principles that must be respected:

- No use of HU below the pinch;
- No use of CU above the pinch;
- Do not transfer energy trough pinch.

Based on the CS and HS it is represented the cold composite curve (CCC) and the hot composite curve (HCC), respectively [Figure 1]. From these curves it is possible to obtain the maximum heat recovery and the minimum consumption of CU ($Q_{C,min}$) and HU ($Q_{H,min}$). [2-6]

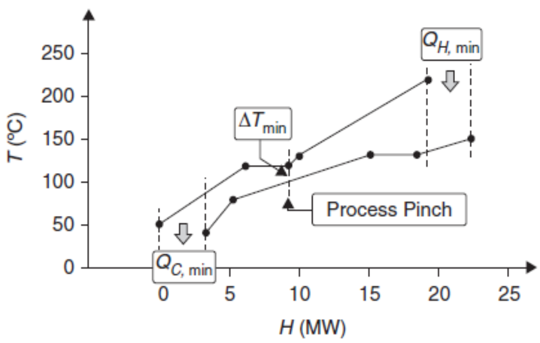

Figure 1 - HCC (above) and CCC (below). [4]

Knowing the minimum consumptions, the heat exchanger network (HEN) is represented for the minimum energy recovery (MER) and compared with the current HEN. Even though this MER HEN corresponds to the optimal energy consumption, it isn't the optimal scenario for the minimum investment. So, for the HEN retrofit it should be looked for a HEN with minimum global cost, which involves the energetic and the capital costs. [4]

Although the retrofit of the HEN is the focus of this methodology, there is also the possibility to rearrange the utilities system. For that purpose, it is represented the global composite curve (GCC) (Figure 2), where the pockets are identified, corresponding to zones where the excess of heat of HS is transferred to CU at lower thermal levels. In this curve it is possible to study the substitution of a HU with a higher thermal level for another with lower level, that should have lower cost. In the case of CU, one with lower thermal level can be replaced for one with higher level. [2-6]

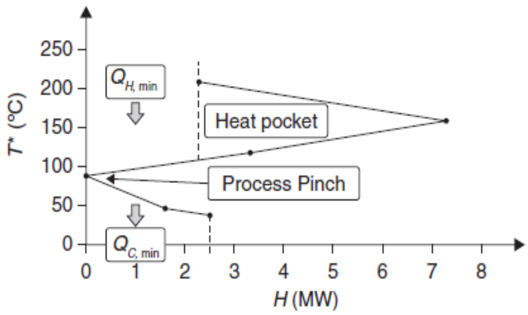

Figure 2 - GCC. [4]

Due to the complexity of industrial processes there are software that allow to implement this methodology, like FI²EPI from IST / Universidade de Lisboa (free software) and Aspen Energy Analyzer (commercial software).

3. Process Description

This methodology for heat integration was applied to the 1,3-butadiene and ETBE plants of Repsol Polímeros in Sines, Portugal.

1,3-Butadiene is a diolefin which has a high market value and is specially used in the synthetic rubber production. This compound is extracted from C4 fraction provided by the steam-cracking plant of the complex using dimetilformamide (DMF) as solvent. This plant is divided into four different zones. The first section is the 1st extractive distillation which contains one distillation column, one stripping column and one compressor. The second section is the 2nd extractive distillation which has one extractive column, one distillation column only with reboiler and one stripping column. In the third section occurs the purification of butadiene with two distillation columns and the 1,3-butadiene is obtained. There is a fourth section to accomplish solvent purification.

ETBE is an ether used as an oxygenate additive for gasoline. In this plant ETBE is obtained by the catalyzed reaction between ethanol and isobutene, contained in the Refinate I stream obtained in the 1,3-butadiene plant. This unit contains two reactors followed by a distillation column where the ETBE is obtained. After this column there is a liquid-liquid separation column to recover the ethanol with water. Following this column there is a distillation column to separate these ethanol/water mixture, with the purpose of recycling the individual compounds into the process.

4. Simulation

Both processes were simulated using the process simulation software Aspen Hysys. For the BTD simulation the Peng-Robinson model was chosen and for the ETBE simulation were used the NRTL and the UNIQUAC models, where the last one was needed for the ethanol distillation column.

It should be noted that real operating data from a specific day was used to simulate the process. However, the processes don't occur at stationary state and some fluctuations are expected if data from another day is used.

For the simulation, the available utilities in the plants were used. There are three HU and four CU, which are presented in Table 1.

Table 1 – Available utilities and respective temperatures.

	T_i (°C)
Medium Pressure Steam (MP)	192.0
Low Pressure Steam (LP)	165.0
Hot Condensates (HC)	63.0
Cold Condensates (CC)	82.0
Circulating Water (CircW)	45.0
Dry Cooler (DC)	20.0
Cooling Water (CW)	18.0

In order to analyze the amount of energy involved in each plant, a graphic with the utilities consumption and the heat exchanged between process streams (HEPS) was represented (Figure 3).

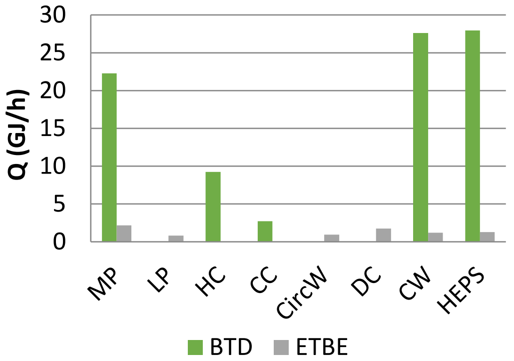

Figure 3 - Heat consumption for both plants.

It is evident that the amount of energy consumed in the BTD plant is much higher than in the ETBE plant. Regarding utilities consumption in BTD unit, CW and MP are the most commonly consumed ones. Nevertheless, the HEPS represents 31% of all energy exchanged in the plant, which indicates that this plant has already several solutions implemented for heat recovery. On the other hand, ETBE has only 16% of HEPS. The most frequently used utilities in this plant are MP and DC. Due to its higher cost, MP represents 88% of the total operational cost of BTD unit (3.1M€/ano) and 79% for ETBE unit (338.1k€/ano).

5. Heat Integration

5.1. BTD Plant

The PS characterization was retrieved from simulation and is presented in Table 2 with the initial temperature (T_i), the final temperature (T_f), the heat capacity (MCp) and the heat duty (Q). The main reason for the high integration observed in this plant is the existence of a solvent circuit (SC). In this circuit the DMF recovered from stripping columns is cooled down from 162.3ºC until 40.0ºC, due to the heat exchange with five process streams and, at the end, with CW. The SC is illustrated in Figure 4.

Table 2 – Streams caracterization for BTD plant.

Streams	T_i (ºC)	T_f (ºC)	**MCp (10⁴ kJ/kg.ºC)**	**Q (10⁵ kJ/h)**	**HU / CU**
Refinate I	26.0	24.9	383.9	43.8	CW
Vapor 1st Strip	103.6	66.0	7.2	27.1	CC
Vapor 1st Strip E0105	63.6	35.0	5.5	15.8	CW
Inter-Stages compressor	76.6	40.0	3.4	12.5	CW
Vapor 2nd Ext	30.3	29.7	1088.4	62.0	CW
Liq 2nd Ext E0202	120.0	73.0	3.4	15.8	-
BTD Rec Col Feed	73.0	71.7	2.4	0.3	CW
Vapor 2nd Strip	121.0	37.0	3.0	25.0	CW
Vapor 1st Frac	35.6	35.0	464.8	27.9	CW
Vapor 2nd Frac	33.9	33.8	6110.8	73.3	CW
Butadiene	33.8	24.0	1.0	0.9	CW
C4 Fraction	24.6	58.7	16.0	54.4	DMF
Liq 1st Ext E0102B	93.0	113.5	38.5	78.9	DMF
Liq 1st Ext E0102B	73.0	99.8	34.3	92.0	DMF
Liq 1st Ext E0103	112.0	117.0	78.1	39.1	MP
Liq 1st Strip	160.0	162.3	478.3	110.0	MP
Plate to E0202	56.0	75.0	8.3	15.8	DMF
Liq 2nd Ext	71.0	120.0	7.4	36.3	MP
Liq BTD Rec Col	108.0	138.0	7.0	21.0	MP
Liq 2nd Strip	160.0	161.7	96.9	16.5	MP
Liq 1st Frac	38.6	51.9	22.1	29.4	DMF
Liq 2nd Frac E0304	45.0	45.4	2103.6	92.6	HC
Liq 2nd Frac E0305	38.7	38.7	2958.7	8.9	DMF
DMF to E0102B	162.3	130.0	24.4	78.9	-
DMF to E0102C	130.0	90.0	23.0	92.0	-
DMF to E0305	90.0	86.0	22.2	8.9	-
DMF to E0110	86.0	45.0	13.3	54.4	-
DMF to E0302	86.0	50.0	8.2	29.4	-
DMF to E0108	46.9	40.0	20.7	14.3	CW

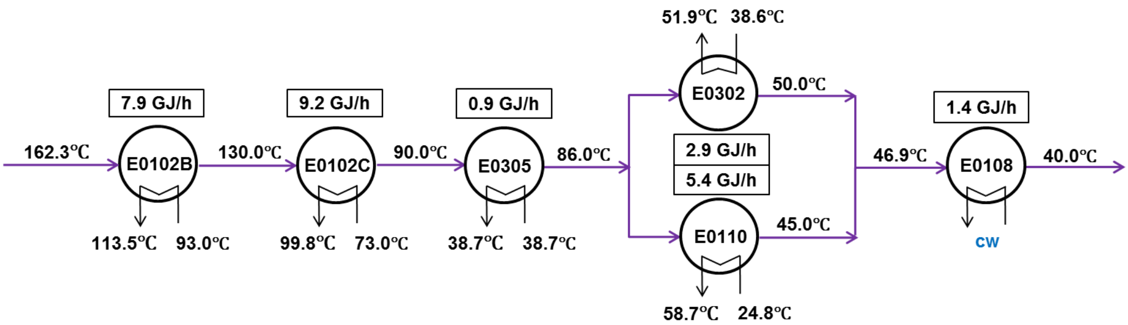

Figure 4 - Current SC with thermal levels and duty.

The next stage was analysing the current HEN for a ΔT_{min} of 10ºC obtained by the software Aspen Energy Analyzer. This network currently has a total of 23 heat exchangers (HE): 11 coolers, 6 heaters and 6 with exchanges between PS. The HEN's analysis showed a pinch process at 41.5ºC and a pinch utility at 87.5ºC. The main problem of cross pinch in this HEN is the use of CW in several condensers of distillation columns.

Representing the composite curves (Figure 5) it was possible to identify the minimum consumption of HU and CU (24.3 and 23.0 GJ/h, respectively). The real consumptions are higher than these, namely 31.5 and 30.3 GJ/h, which means that there is a possibility to reduce both HU and CU in 23% and 24%, respectively.

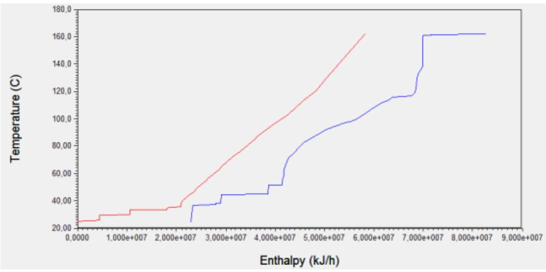

Figure 5 – Current HCC (red) and CCC (blue).

With the study of the HEN and the composite curves it was demonstrated that this unit has potential for energy recovery. For this purpose, several projects for heat integration were studied. However, in this work only the ones that are included in the final heat integration proposal are presented. For all these studies the estimation of the new heat exchanger prices was done using a cost estimation tool, developed by the engineering company Matches [7]. These prices were actualized for the year 2015 and converted to €. It is also important to refer that the investment was calculated assuming that the heat exchanger price represented 55% of the total investment.

Project BTD1 – MP substitution by LP

Due to the high value of MP, this utility is the major reason for the high energetic costs. So, its consumption must be reduced. In this project the possibility of its substitution by LP is studied, since this utility with lower thermal level, has consequently, a lower cost. In a first approach, it was verified that there is a possibility of a thermal limitation in the strippers reboilers, since those work at approximately 162ºC. However, the current plant has a ΔT_{min} of 3ºC and these reboilers were projected for a ΔT_{min} of 5ºC, reason why in this study this was not considered as a limitation. Nevertheless, the temperature records should be studied for a more detailed analysis.

The second approach was to verify if the installed reboiler had sufficient heat transfer area to perform the heat exchange with LP. The conclusion was that only the 1st stripper reboiler (E0106) needs an extra area (69m^2). Thus, it is suggested the use of a new reboiler (E0106A) in parallel with E0106. This new HE will cost 25.3k€, which corresponds to an investment of 46.0k€. Therefore, it is possible to recover this investment in 1 month and 11 days.

Project BTD2 – Pre-Heating of C4 Fraction with Condensates to the Thermoelectric Unit in the Complex

The HEN also showed that the C4 fraction pre-heater (E0110) is crossing pinch, reason why this study was done. Currently, the C4 fraction is pre-heated with DMF in the HE E0110 and the Condensates to Thermoelectric Central (Central C) are cooled down there. In Table 3 the current E0110 conditions are presented.

Table 3 - Current conditions of E0110.

	Streams	T_i (ºC)	T_f (ºC)	Q (GJ/h)
E0110	DMF to E0110	86.0	45.0	5.4
	C4 Fraction	24.6	58.7	

The Central C flow corresponds to all the steam used as utility that condensates, and corresponds to 11.3t/h. This flow is sufficient to give to C4 fraction enough heat to heat up until 33.0ºC, as presented in Table 4.

Table 4 - New HE conditions for Project BTD2.

	Streams	T_i (ºC)	T_f (ºC)	Q (GJ/h)
E0110A	Central C C4 Fraction	63.0 24.6	34.6 33.0	1.3
E0110	DMF to E0110 C4 Fraction	86.0 33.0	55.2 58.7	4.1

In Figure 6 a schematic diagram for this project is presented. The new HE E0110A is represented in red.

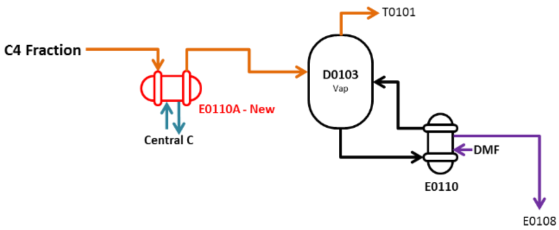

Figure 6- Representative scheme of Project BTD2.

The new HE E0110A needs 119m^2 of heat transfer area, corresponding to a price of 46.7k€ and an investment of 84.9k€. This project has no payback time because this will be estimated with the Project BTD6.

Project BTD4 – Integration between the liquid stream of 2nd extractive column and the vapor stream of 2nd stripper

From the analysis of thermal level and heat duty of all streams, it was verified that the vapor stream of 2nd stripper has enough heat and temperature to heat the liquid stream of 2nd extractive column. In Table 5 the 2nd extractive reboiler (E0203) and the 2nd stripper condenser (E0206) are presented.

Table 5 - Current conditions of E0203 and E0206.

	Streams	T_i (ºC)	T_f (ºC)	Q (GJ/h)
E0203	MP Liquid 2nd Ext	- 71.0	- 120.0	3.6
E0206	Vapor 2nd *Strip* CW	121.0 -	37.0 -	2.5

Due to the thermal level the only possible way to integrate these streams is in series with a new HE (E0203A), represented in red in Figure 7.

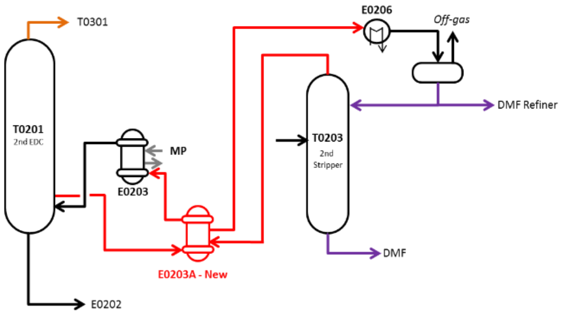

Figure 7- Representative scheme of Project BTD4.

With this integration is possible to recover 33% of the steam consumed in the E0203 and 48% of CW consumed in the E0206. The new HE conditions are presented in Table 6.

Table 6 - New HE conditions for Project BTD4.

	Streams	T_i (ºC)	T_f (ºC)	Q (GJ/h)
E0203A	Vapor 2nd *Strip* Liquid 2nd Ext	121.0 71.0	81.0 87.1	1.2
E0203	MP Liquid 2nd Ext	- 87.1	- 120.0	2.4
E0206	Vapor 2nd *Strip* CW	81.0 -	37.0 -	1.3

The new HE E0203A needs 152m^2 of heat transfer area with a price of 55.2k€, which represents an investment of 100.4k€. This project has a total saving of 147.3k€ (MP+CW), resulting in a payback time of 0.68 years. If it is considered that the BTD1 is implemented before this project, the total saving is 103.8k€ (LP+CW). For this situation the payback time is 0.97 years.

Project BTD6 – Integration of SC with 1st extractive reboiler + BTD2

Since the DMF stream, after being recovered in the stripping columns, has a high thermal level and a huge amount of energy (25GJ/h), this represents a good possibility for integration. Due to the release of 1.3GJ/h from this stream with the Project BTD2, it is possible to integrate the SC at 162.3ºC with the reboiler of the 1st extractive distillation column. The current conditions of this reboiler (E0103) are presented in Table 7.

Table 7 - Current conditions of E0103.

	Streams	T_i (ºC)	T_f (ºC)	Q (GJ/h)
E0103	MP Liquid 1st Ext E0103	- 112.0	- 117.0	3.9

Due to the thermal level it is conceivable to integrate these streams in parallel in a new HE (E0103B), as showed in Figure 8.

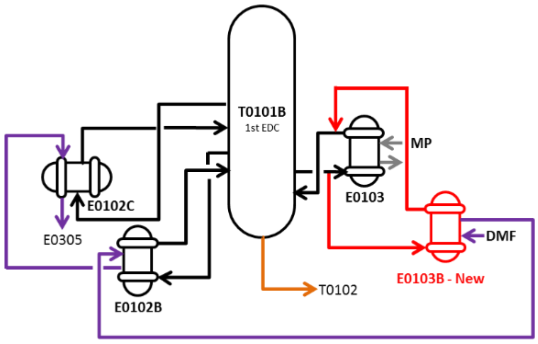

Figure 8 - Representative scheme of Project BTD6.

To calculate the new HE conditions, presented in Table 8, it was considered a need of $\Delta T \geq 10$ºC, reason why the flow fraction of E0302 and E0110 changes from 0.380 and 0.620 to 0.456 and 0.544, respectively. With this integration it is possible to save 46% of steam in E0103 and 29% of CW in the final SC cooler. The new conditions of SC are represented in Figure 9.

Table 8 - New HE conditions for Project BTD6.

	Streams	T_i (ºC)	T_f (ºC)	Q (GJ/h)
E0103B	DMF Liquid 1st Ext E0103	162.3 112.0	154.9 117.0	1.8

The new HE E0103B needs 170m^2, which has a price of 43.4k€. The saving cost for this project is 220.1k€ (MP+CW), corresponding to a payback time of 0.74 years. Considering that the Project BTD1 is previously implemented, the saving cost is 154.3k€ (LP+CW) and the payback time will be 1.06k€.

5.2. ETBE Plant

From the simulation the PS characterization was retrieved (Table 9). As for BTD plant, the HEN for 10ºC of ΔT_{min} using the Aspen Energy Analyzer was represented too. This network currently has a total of 12 HE: 7 coolers, 3 heaters and 2 with exchanges between PS. The HEN's analysis showed a pinch process at 128.4ºC, which main cross pinch problem is the use of LP in the pre-heater of the 1st reactor feed. There are three utility pinches at 22.5, 45.3 and 160.0ºC with the main problem of cross pinch in the use of DC in the distillation columns.

To determine the minimum consumption on HU and CU the composite curves were represented (Figure 10), obtaining 2.3 and 3.2 GJ/h, respectively. The current consumption is higher, namely 3.0 and 3.9 GJ/h, which represents a potential of reduction of 42% and 8%, respectively.

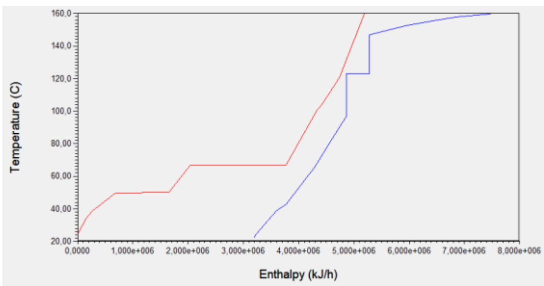

Figure 10 – Current HCC (red) and CCC (blue).

Like in the BTD plant, several projects for heat integration were studied. However, only the one that was chosen to integrate the final proposal is presented.

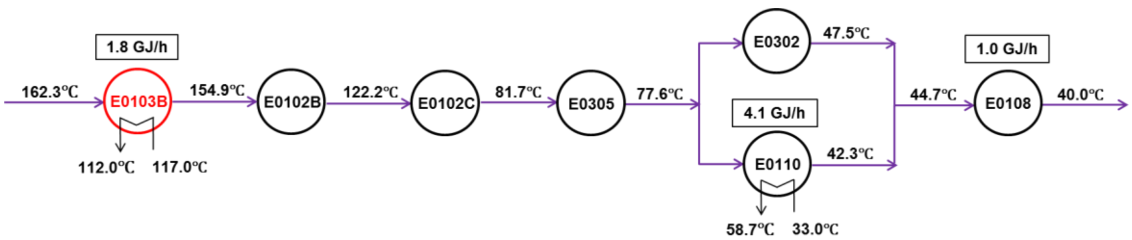

Figure 9 - Proposal SC for Project BTD6.

Table 9 - Streams caracterization for ETBE plant.

Streams	T_i (ºC)	T_f (ºC)	MCp (MJ/kg.ºC)	Q (10^5 kJ/h)	HU / CU
R0902 Feed	50.3	39.0	166.7	1.9	CW
Vapor T0902	67.1	67.0	123369.8	17.1	DC
T0903 Feed	67.0	24.0	71.1	3.1	CW
Washing Water T0903 E0907	123.5	83.2	63.0	2.5	-
Washing Water T0903	83.2	34.0	63.2	3.1	CW
Vapor T0904	109.7	101.0	55.0	0.5	DC
ETBE E0903	160.0	66.7	110.4	10.3	-
ETBE	66.7	25.0	96.1	4.0	CW
R0901 Feed	22.0	43.0	193.2	4.1	LP
T0902 Feed	39.0	97.0	177.7	10.3	-
Liq T0902	146.8	160.0	1658.6	21.8	MP
Liq T0903	24.6	65.0	63.0	2.5	-
Liq T0904	123.4	123.5	217751.9	4.1	LP

Project ETBE1 – Substitution of LP consumed on the pre-heater of the 1st reactor feed by CircW

Since this HE (E0901) was referenced as a cross pinch problem it was studied a scenario to resolve it. Nowadays the 1st reactor is kept in isotherm conditions due to the CircW. This circulates in a close circuit, so it needs to be cooled down, currently at a DC (E0910). The idea in this project is to cool down this utility by heating up the feed to the reactor. The current conditions for this two HE are presented in Table 10.

Table 10 - Current conditions of E0901 and E0910.

	Streams	T_i (ºC)	T_f (ºC)	Q (10^5 kJ/h)
E0901	LP	-	-	4.1
	R0901 Feed	22.0	43.0	
E0910	CircW	55.0	45.0	17.1
	DC	-	-	

From Table 10 it is possible to conclude that the stream R0901 feed doesn´t have enough heat to cool down all the CircW. So, it is projected a parallel design with E0910, as showed in Figure 11. The E0901 (blue) is maintained for start-up needs and a new HE (E0901A) (red) is implemented. The new HE conditions for this project are presented in Table 11.

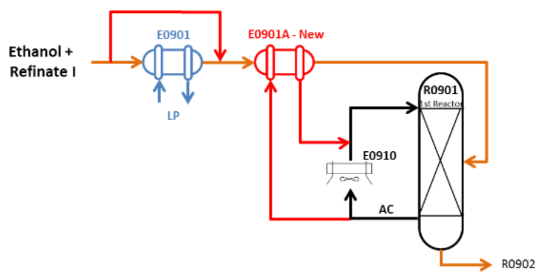

Figure 11 - Representative scheme of Project ETBE1.

Table 11 - New HE conditions for Project ETBE1.

	Streams	T_i (ºC)	T_f (ºC)	Q (10^5 kJ/h)
E0901A	H CircW	55.0	45.0	4.1
	R0901 Feed	22.0	43.0	
E0910	H CircW	55.0	45.0	13.1
	DC	-	-	

The new HE E0901A needs 6m^2, which has a price of 9.8k€ and an investment of 17.7 k€. Since this project has a LP saving of 25.8k€, the payback time is 0.69 years.

5.3. Final Heat Integration Proposal

The projects contained in this final integration proposal are the ones showed before, since for all the studied projects these were the ones economically more favourable. In Table 12 all the projects and the total saving, investment and payback times are resumed.

The main conclusion is that the final proposal is economically viable since the payback time is lower than 2/3 years, which is the limit time to consider a project economically viable in this industry. A sensibility analysis was also performed and even for the triple of the investment the project still remains economically viable (payback time=0.99).

The new heat consumption, Figure 12, was compared with the current one, presented in Figure 3.

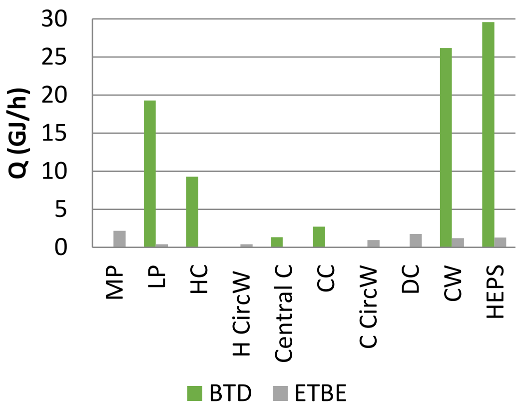

Figure 12 – New heat consumption for both plants.

The heat consumption in BTD plant is still higher when comparing to the ETBE plant. For the BTD plant an increment of 6% in HEPS was verified, which represents the increase in the global consumption since there were not changes in this utility for the ETBE plant. In Figure 13 the utilities consumption for both units for the current case and the final proposal are presented.

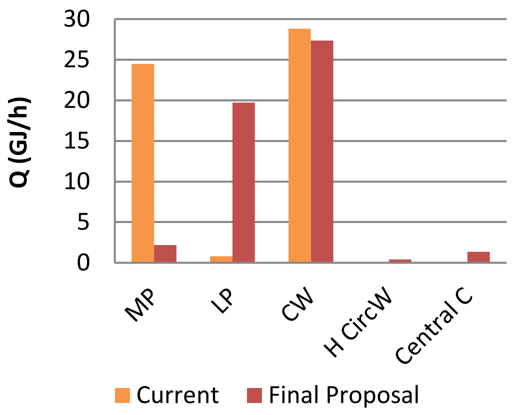

Figure 13 - Heat consumption for the new utilities and for the changed utilities.

The main impact is related to the high decrease in the MP consumption. Currently it represents 25% of the total heat consumption on both plants. For the final proposal, it represents only 2%. This decrease in MP was accomplished with the increase in the LP consumption. Currently this utility represents 1% of total heat consumption for both units and in the final proposal it represents 20%.

To study the economic impact of the proposed changes, in Figure 14 the changes in the total operational cost due to the alterations in the main utilities were represented.

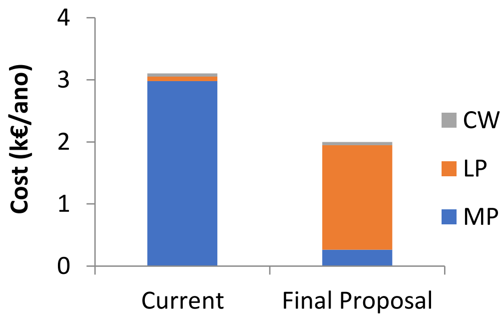

Figure 14 - Total operational cost for the current scenario and for the proposed one.

Table 12 - Resume of final heat integration proposal.

Projects	Saving (k€/year	New HE	Investment (k€)	Payback Time (year)
BTD1	705.2	E0106A	46.0	0.07
BTD4 with LP	103.8	E0203A	100.4	0.97
BTD6 with LP	154.3	E0103B + E0110A	163.7	1.06
ETBE1	25.8	E0901A	17.7	0.69
Total	**989.1**	**-**	**327.8**	**0.33**

The higher changes were in the cost of MP in the BTD plant, that currently costs 2.7M€/year and was substituted by LP that for this proposal has a cost of 1.6M€/year in this plant. The total annual operational cost proposed for this plant is 2.0 M€. For the ETBE unit the changes were lower since the LP cost changed from 69.7k€/year to 35.1k€/year. However, for this plant MP remains the utility with higher costs. The total annual operational cost proposed for this plant is 303.5k€, which stills lower than the BTD cost.

Considering the three utilities there is a 32% decrease since the current cost of both units is 3.4M€/year and for this proposal it becomes 2.3M€/year. The substitution of utilities was the main driver for this reduction (74%), essentially the replacement of MP for LP (97%).

6. Conclusions and Future Work

This study was carried out for the 1,3-butadiene and ETBE plants of Repsol Polímeros at Sines Petrochemical Complex. It had as main goal the reduction on external heat consumption in order to decrease the operational cost in both plants. For this purpose, Aspen Hysys was used to simulate these two processes and the simulation results extracted to Aspen Energy Analyzer. In this software was studied the heat integration using the pinch technology. In Aspen Energy Analyzer the current HEN and the composite curves for both units were obtained. After that, several scenarios to integrate these plants were studied, by recovering circulating energy, as well as substituting utilities.

For the BTD plant the main conclusion was that it is imperative to reduce the consumption of MP, since this is the main reason for the high operational cost of this plant (2.7M€/year). The final proposal has 4 projects: (1) substitution of MP for LP in BTD plant; (2) integration of the liquid stream of the 2nd extractive distillation column with the vapor stream of the 2nd stripping column; (3) integration of solvent circuit with the reboiler of the 1st extractive distillation column as well as the implementation of a C4 fraction pre-heater with condensates for Thermoelectric Central of the Complex; and (4) substitution of the LP consumed in the pre-heater of the 1st reactor feed for CircW. This final proposal has a saving in 989k€ and an investment of 328k€. For this reason, it is estimated a payback time of 4 months and 25 days.

As future work the study to implement a heat pump in the stripping columns is suggested, due to the high consumption of MP and the thermal level. Other suggestion is the study to replace the use of dry coolers in the ETBE plant.

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