CHEMICAL ENGINEERING TRANSACTIONS

VOL. 94, 2022

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Petar S. Varbanov, Yee Van Fan, Jiří J. Klemeš, Sandro Nižetić

ISBN 978-88-95608-93-8; **ISSN** 2283-9216

DOI: 10.3303/CET2294102

Energy-Saving Potential of an Existing Monomer Production by Combined Process and Inter-Plant Integration

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The problem of efficient use of energy is crucial for the industry as it affects final revenue and environmental issues. Petrochemical sites have extensive utility networks that are consuming and distributing energy to processes. This paper proposes the approach for analysing an interplant integration with the use of intermediate utilities applying individual ΔT_{min} for all utilities. It was performed by the use of real temperature when plotting Total Site profiles, optimising the temperature of intermediate utility and rearranging remaining utility demands with existing utility. The case study analysed monomer production at the petrochemical site and assessed the potential for utility reduction by improving the existing process to process recovery and interplant integration. The cooling capacity reduction is 31 % and heating demands were reduced by 80 %. The additional option for power generation was considered.

1. Introduction

The transition to clean and sustainable energy was motivated by the last epidemic and political crisis. Success in replacing fossil fuels is economically viable by cutting primary energy demands. In industry, as the biggest energy consumers and pollutants, it comes via energy efficiency of existing processes or new concepts for newly built. Utility system optimisation helped reduce energy consumption greatly, as reported by Sun et al. (2017). The concept for the analysis of site utility systems was initially proposed by Dhole and Linnhoff (1993) and updated later by Klemeš et al. (1997) to extend the targets for utility consumption, cogeneration, and emission reduction. The field has been seriously developed and applied in industry and other sectors. For instance, the Swedish chemical industry, accounted for 30-50 % savings as reported by Eriksson et al. (2018). Potrč et al. (2021) tried to demonstrate the possibility to achieve the energy transition goals by analysing synergies between sectors for the overall efficiency of the energy system. Sensitivity analysis of the Total Site (TS) assessed the effect of the performance of the centralized trigeneration system on the industrial plant's maintenance shutdown and production changes (Jamaluddin et al., 2020). The extended approach allowed integrated extended locally integrated energy sectors with thermal energy storage and batteries (Lee et al., 2020). Mehdizadeh et al. (2022) proposed a graphical tool to calculate the exergy destruction and losses within TS. Despite developments, there are still some issues that need to be investigated. Initial graphical method Total Site Profile (TSP) construction presumes unified ΔT_{min} of individual processes under consideration. Varbanov et al. (2012) solved this problem by a double shifting of Grand Composite Curve (GCC) segments and resulting TSP with utility GCC. The utility temperature remains fixed for the particular considered process as well, e.g., ΔT_{min} between all utilities and TSP. Boldyryev et. al 2014 proposed optimisation of intermediate utility (IMU) temperature based on heat transfer area and later updated with unit numbers (Boldyryev et al., 2021). But the use of the varied temperature of IMU supposes different ΔT_{min} for each utility. The same consideration can be also applied to other utility streams of TS. The novelty and relevance of this study lay down in consideration of TSP at real temperatures and supplementary new methodological changes. First, the real TSP temperatures are considered that allow setting different ΔT_{min} between utilities and TSP. This provides flexibility for utility use at the TS level. Second, steam expansion sections at Total Site Heat Recovery (TSHR) are assessed at the enthalpy block jointly with IMs usage. Both improvements were developed and tested when analysing monomer production by pyrolysis of gas

Paper Received: 22 April 2022; Revised: 10 May 2022; Accepted: 11 July 2022
Please cite this article as: Boldyryev S., Gil T., Khussanov A., Krajačić G., 2022, Energy-Saving Potential of an Existing Monomer Production by Combined Process and Inter-Plant Integration, Chemical Engineering Transactions, 94, 613-618 DOI:10.3303/CET2294102

and gasoline feedstock. The case study demonstrated that utilising existing methodology its drawbacks can be found, and the development of local methods and improvements are needed.

2. Methods

The main achievement of this research is the finding of maximum energy recovery potential by process-to-process and inter-plant integration of monomer production. It was achieved by updating the Total Site methodology. Intermediate utilities and steam expansion sections are used instead of existing utilities. It allows increasing heat recovery at the Total Site level and assesses maximum power production. The method proposed in this paper presumes to find maximum heat recovery and cogeneration potential using intermediate utilities (IMU). The selection of IMU temperature is based on optimization of its temperatures within enthalpy blocks accounting for heat transfer area and a number of heat exchanger units. Since each IMU has different ΔT_{min} with Source/Sink profiles the Total Site profiles are built for real temperatures. As result, the Total Site profiles accounting for IMU for heat recovery extended with cogeneration potential and additional capital cost are compared.

The methodological steps can be following: 1) Data Extraction and identification of direct integration possibility from process A to process B; 2) setting the Grand Composite Curves (GCC) of considered processes (Dhole and Linnhoff, 1993); 3) eliminating the recovery pockets and local utility (Klemeš et al., 1997); 4) changing the segments to real temperatures; 5) combining the Total Site Profiles (TSP) with real temperatures; 6) putting TS profiles at min dT and max recovery (analogues to Composite Curves (CC)); 7) decomposition of overlapping TS segments into enthalpy blocks (Boldyryev et al., 2021); 8) finding minimum heat transfer area and potential of power generation within each enthalpy block; 9) merge adjacent enthalpy blocks and repeat the previous step; 10) final distribution of IM utilities, hot and cold utilities, power generation potential, additional heat transfer area, and capital cost targets for steam turbines, utilities are placed with real temperatures.

The next assumptions are used to simplify the final model: 1) all heat exchangers for TSHR are considered the same construction type, pressure and temperature level; 2) Pressure drop does not account; 3) steam turbines applied within enthalpy blocks that are selected/merged by minimisation of heat transfer area; 4) enthalpy block has one steam turbine if considering electricity generation; 5) isentropic efficiency of new steam turbines accepted as 85 %; 6) all steam turbines are described with the same cost law.

The modelling algorithm presented in this paper treats the next main equation set. Heat transfer area in enthalpy blocks optimised from Eq(1), full optimisation procedure see in Boldyryev et al. (2021).

$$\mathrm{A_k} = \min_{\mathrm{t_1 < t_{IM} < t_2}} \left[\frac{1}{\Delta \mathrm{T_{ln}^H}} \cdot \left(\sum_{\mathrm{i=1}}^{\mathrm{n}} \frac{\mathrm{q_i}}{\mathrm{h_i}} + \frac{\mathrm{q_{IM}}}{\mathrm{h_{IM}}} \right) + \frac{1}{\Delta \mathrm{T_{ln}^C}} \cdot \left(\sum_{\mathrm{j=1}}^{\mathrm{m}} \frac{\mathrm{q_j}}{\mathrm{h_j}} + \frac{\mathrm{q_{IM}}}{\mathrm{h_{IM}}} \right) \right]_{\mathrm{k}} \tag{1}$$

The number of heat transfer units in enthalpy blocks is calculated from Eq(2):

$$N_k = n_k^h + n_k^c \tag{2}$$

The steam turbine costs were obtained from the relation presented in Kwak D.-H. et al. (2014):

$$\log C_T = 0.6032 \cdot \log W_T + 3.383 \tag{3}$$

The capital cost of heat exchangers is based on heat transfer area and found for shell and tube units of carbon steel with pressure specifications up to 30 bar and temperature range up to 300 °C. The correlation is adopted based on the Smith (2016) and applying coefficients according to Chemical Engineering Indexes and Marshall and Swift, Eq(4):

$$C_{HE} = 3999.3 A^{0.68} \tag{4}$$

3. Case study

The case study shows the analysis of existing monomer production that is part of the petrochemical site. The gasoline and ethane are used for high-temperature pyrolysis to obtain ethylene, propene, and other related products. The simplified block diagram of the investigated process is shown in Figure 1. 127 process streams, 66 energy streams and 66 process units were under consideration. The process is split into two units, the first is pyrolysis and gas compression and the second is gas fractioning and condensate processing. The distance between these units and features of technology limits the direct process integration. Stream properties and vapour-liquid equilibrium were simulated by UniSim Design.

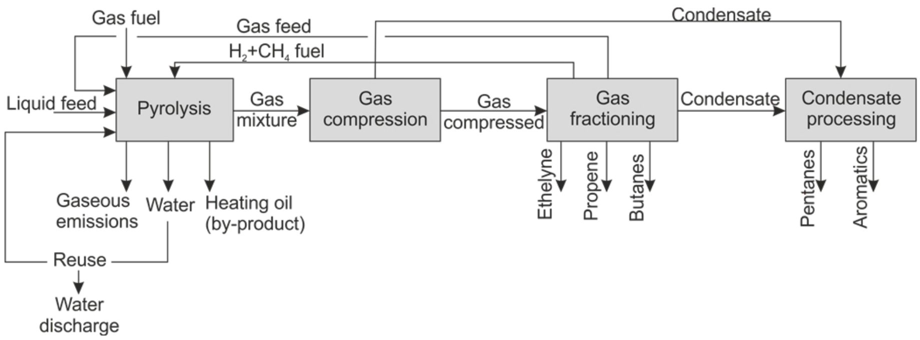


Figure 1: Simplified block diagram of investigated monomer production

Existing process utility is steam 4, 12, 15, 25, 100 bar, flue gases, cooling water, cooling air, ethylene, propylene. The circulating hot water is used for inter-plant integration and utilized heat of pyrolysis gas for heating process streams. ΔT_{min} between process and utility streams is set 6 °C, as identified for an existing process. ΔT_{min}(TSP) was accepted at 10 °C due to maximum potential should be found and the existing heat exchangers can effectively operate at ΔT_{min} of 5 °C.

4. Result and discussion

GCC of considered processes is shown in Figure 2, they demonstrated the utility targets that should be covered by the utility. Pyrolysis uses high-temperature utility and gas separation is situated in a low-temperature area.

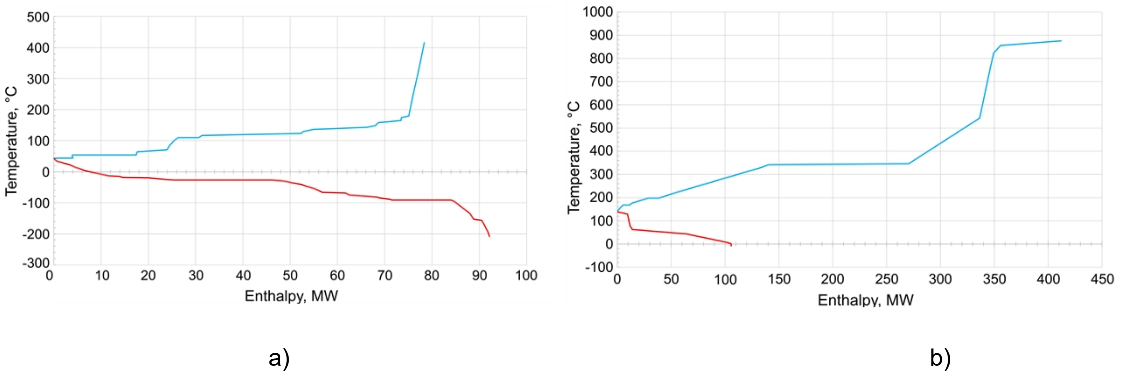


Figure 2: GCC of investigated processes: a) gas and condensate processing; b) pyrolysis and gas compression

Existing direct process integration and local process utility were eliminated from the GCCs elements to build the TSP. The TSP of monomer production built by the approach of Varbanov et al. (2012) is shown in Figure 3, ΔT_{min} between process and utility streams is 6 °C. The existing utility distribution demonstrated the impossibility to utilize the recovery potential without changing the utility-process connection. Existing interplant integration by circulating hot water was increased by 24.8 MW to heat the bottom of distillation columns and the TSP was modified. The TSPs were rebuilt for real profile temperatures as shown in Figure 4 and TSHR was maximized by replacing existing utilities by IMU with the individual ΔT_{min} between TSP and utility. The minimum temperature approach for Total Site was set at 10 °C. The remaining utility demands are satisfied by available existing utilities. The comparison of utility demands of the existing process and improved TSHR is presented in Table 1. Cooling capacity is reduced by 31 % and heating demands can be cut by 80 %. The TSHR was decomposed in enthalpy blocks and IMUs were selected optimising temperatures and merging blocks. The results are shown in Figure 5a where 11 blocks were identified and hot water and steam with different temperatures were used as IMUs. Heat recovered by IMU is 47.78 MW and it needs a heat transfer area of 5,462 m^2, the detailed distribution of IMU area is shown in Table 2. An additional option for electricity generation by utilizing the expansion potential of steam is demonstrated in Fig. 5b. Total electricity production within enthalpy blocks 8-11 is 235.2 kW and it needs capital investments for 4 steam turbines at 108,472 USD/y, accounting 5-y project and a fractional interest rate of 10 %. When applying the option for electricity generation above the TS Pinch, the heat transfer area within enthalpy blocks No. 8-11 is increased by 3,586.9 m^2 (88.5 %).

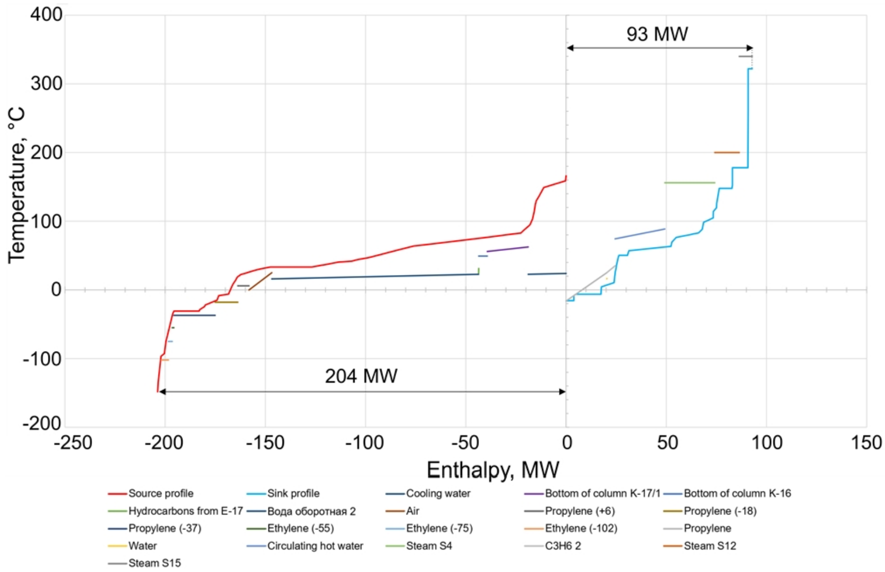


Figure 3: Total Site profiles of monomer production with existing utilities (according to Varbanov et al., 2012)

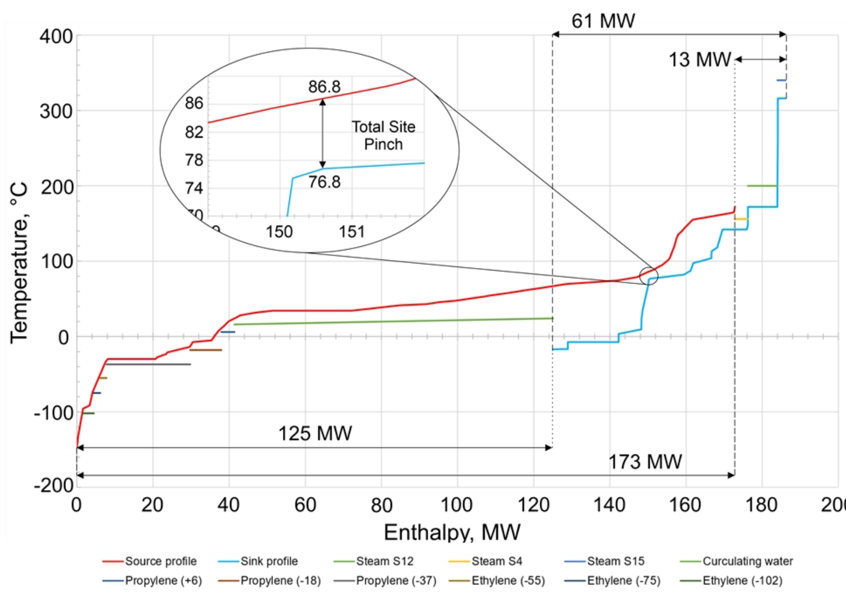
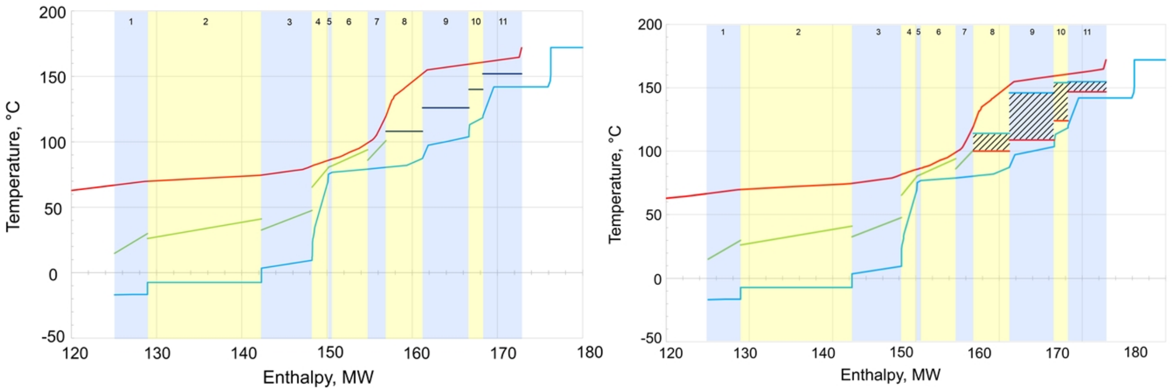


Figure 4: Total Site profiles built by proposed approach and maximizing Total Site Heat Recovery

Proposed changes in TS representation with real profile temperatures provide constructing the TSHR with minimum heat transfer area and reducing the number of utility Pinch(es) that might be beneficial for utility network design. This paper defines the maximum heat recovery potential of interplant integration, but the amount of heat recovered can be an objective for further optimisation finding a compromise between energy-saving, generation and investments. The joint optimization of steam turbines number and IMU is an objective of future works. It is important when optimising electricity generation by accounting for supply and demand including energy price variation. Especially when energy prices go high and make the utilisation of waste heat economically viable. On the other hand, it cuts the primary energy supply, both, for heating and cooling. The cooling problem became even more important due to local and global changes in climate conditions. Initially, the current plant layout and equipment were designed for air cooling as a cold utility, and now, it needs extra energy for cooling during the summer period.



a) applying heat recovery via IM utilities; b) applying heat recovery via IM utilities and electricity generation

Figure 5: Total Site Heat recovery of monomer production with merged enthalpy blocks and optimized IM utility

Table 1: Utility heat duty distribution of initial process and TS integration via IM utilities

Utility	T_{Supply}, °C	T_{Target}, °C	Heat duty, MW (Initial process)	Heat duty, MW (TSHR)
Circulating water	-16.2	35.0	122.0	83.7
Air	0.0	25.0	11.4	-
Propylene (+6)	6.0	6.0	5.6	3.4
Propylene (-18)	-18.0	-18.0	11.3	8.2
Propylene (-37)	-37.0	-37.0	20.6	22.0
Ethylene (-55)	-55.0	-55.0	0.8	1.6
Ethylene (-75)	-75.0	-75.0	1.9	1.7
Ethylene (-102)	-102.0	-102.0	5.4	2.9
Total cold utility			**179,0**	**123.5**
Propylene	34.0	-16.2	24.4	-
Hot water	16.2	16.0	0.1	-
Steam 4	156.0	156.0	24.9	3.4
Steam 12	200.0	200.0	12.2	7.7
Steam 15	340.0	340.0	6.4	2.1
Total hot utility			**68.0**	**13.3**

Table 2: Distribution of IM utilities within enthalpy blocks of TSHR

No. of enthalpy block	IM utility	T_{Supply}, °C	T_{Target}, °C	Heat load, MW	Heat transfer area, m2
1		14.9	29.9	3.88	158.0
2		26.1	41.1	13.36	462.3
3	Circulating water	32.6	47.6	5.96	293.1
4		65.4	80.4	1.92	300.8
5		80.7	81.8	0.42	192.7
Total below TS Pinch				**25.54**	**1,406.9**
6	Circulating water	81.8	94.0	4.16	300.8
7		86.0	101.0	2.17	192.7
8		108.0	108.0	4.28	899.1
9	Steam	126.0	126.0	5.46	965.3
10		138.0	138.0	1.62	432.1
11		150.0	150.0	4.55	1265.2
Total above TS Pinch				**22.24**	**4,055.1**

5. Conclusions

This work proposed the modified procedure of Total Site profile construction with real profiles' temperature. The approach allows different temperature approaches for multiple utilities which is essential when using the intermediate utility for Total Site heat recovery. The procedure is demonstrated on real industrial data of petrochemical site focusing on utility distribution and usage. The monomer production unit is analysed and the utility saving potential of combined in-plant and inter-plant integration was defined as 31 % for cooling capacity and 80 % for heating demands, which are also the contribution of emission saving and primary energy. It's mostly related to saving cooling water, refrigerants, and steam saving. The inter-plant heat recovery was maximized using the intermediate utility. The optimised temperature of the intermediate utility requires an additional heat transfer area of 5,462 m^2. Additional option presumes the electricity generation of 0.24 MW needs 88.5 % more heat transfer area and a capital cost of 417,200 USD for steam turbines.

Nomenclature

A_k – minimum heat transfer area of heat recovery of *k* enthalpy interval, m^2
C_E – the price of electricity, USD/kWy
C_{HE} – capital cost of the heat exchanger, USD
C_T – capital cost of steam turbine, USD
h_i – film heat transfer coefficient of *i* process stream, W/(m^2 °C)
h_{IM} – film heat transfer coefficient for intermediate utility, W/(m^2 °C)
h_j – film heat transfer coefficient of *j* process stream, W/(m^2 °C)
k – number of enthalpy interval
i – fractional interest rate, %
n – project lifetime, y
n_i^k – number of hot streams in enthalpy interval
n_j^k – number of cold streams in enthalpy interval
N_k – number of heat exchangers
q_i – heat load of *i* hot stream, kW
q_{IM} – heat load of intermediate utility in enthalpy interval, kW
q_j – heat load of *j* cold stream, kW
t_1 – temperature low bound, °C
t_2 – temperature upper bound, °C
ΔT_{ln}^C – log mean temperature difference for sink side, °C
ΔT_{ln}^H – log mean temperature difference for source side, °C
W_T – electricity generated by a steam turbine, kW

Acknowledgements

This work was supported by the Research Fund of the Republic of Kazakhstan under grant No. AP09260365. Authors acknowladge RES4Industry project that has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N.952936. and European sustainable energy inovation aliance – ESEIA for enebling the participation in RES4Industry project.

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