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Petroleum & Petrochemical Engineering Journal
ISSN: 2578-4846

Retrofit of Refinery Utility System by Total Site Heat Recovery: Practical Arrangements

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Research Article
Volume 2 Issue 6
Received Date: August 26, 2018
Published Date: September 11, 2018

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Abstract

This paper presents an optimisation of heat recovery of refinery site, a setting of utility targets of heating and cooling and indirect heat transfer between industrial clusters. The methodology provides the minimisation of capital cost of utility system retrofit. The optimisation of cost parameters connected with the heat transfer area of steam boilers and heaters, intermediate utility levels and a number of units. A method for calculation of a heat transfer area of intermediate utility heat exchangers is proposed. Minimum temperature approach of Total Site heat recovery is analysed and the number of steam mains, indirect heating loops, heat transfer area of boilers and condensers is calculated. The utility consumption, numbers of required units and material of equipment are analysed to optimise the retrofit investments. The case study shows optimal heat recovery of the refinery site of 1.94 MW. It reduces the consumption of middle-pressure steam by 37.3%, the cooling heat capacity is lowered by 39.6%. The investments of a retrofit project are paid back in 11.96 months.

Keywords: Total Site Analysis; Refinery; Energy Efficiency; Industrial Application

Introduction

The refineries consume the one of largest share of delivered energy amongst all the sectors. a Despite lot of researches and developments of energy efficiency the oil refinery still has a huge potential for reducing energy consumption [1]. The role of energy in industry has become very important than ever due to environmental and economic reasons [2]. This issue has been prioritised due to a new EC goal of energy efficiency that has to be achieved till 2030; it should be improved by 27% [3]. Utility systems of oil refinery may contribute to energy efficiency and utilise of low potential heat across plant facilities as well as intersectional collaboration between utility company, refinery and residential sector [4]. These three part of energy consumers are connected and can be integrated to efficient use of primary energy sources. Total Site integration approach has demonstrated a potential of utility reduction [5], an optimisation of a cogeneration potential [6] and the use of different energy sources [7] including renewables [8].

The energy efficiency improvement is one of the key goals sustainable of development in future. As reported by IEA [9] the industrial energy consumption in 2012 was 28% of overall world energy balance (Figure1). A lot of energy efficiency approaches are based on Pinch Analysis, Mathematical Programming and Life Cycle Assessment as well as combinations and modifications of these methods as reported in 10. Klemeš JJ, et al. [10]. Čuček L, et al. proposed the multi-period synthesis of an optimally integrated regional biomass and bioenergy supply network through a mixed-integer linear programing (MILP) approach [11]. They obtained solutions with optimal selection of raw materials, technologies, intermediate and final product flows, and reduced greenhouse-gas emissions. In Čuček L, [12] presented combination of mathematical programming and life cycle assessment for biomass and bioenergy supply chain. In work [13] the authors delivered the application of Pinch Analysis for chemical plant and shown the reduction of energy consumption on 45%. Besides retrofit studies at site levels, there were several retrofits analysis performed at process level such as heat integration of sodium hypophosphite production [14], refinery [15], bromine production [13], cement production [16], milk powder production [17], cheese production [18], benzene production [19], coke-to-chemicals [20], biofuel production [21] etc.

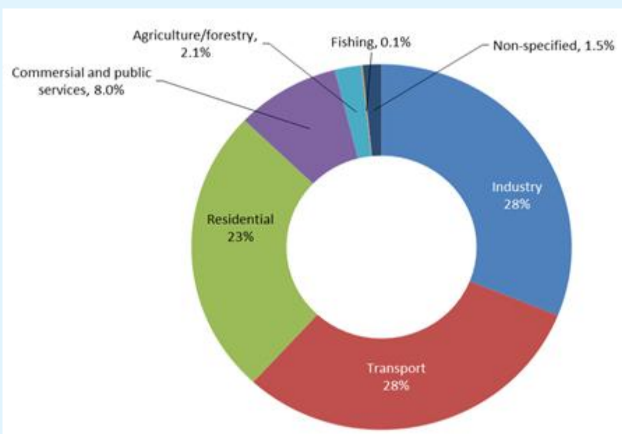

Figure 1: World energy balance (source IEA).

Last time a big progress in energy efficiency of refinery processes was delivered accounting fouling problem [22], economic constraints [23] and more attention should be paid to site level. Firstly, it allows decreasing the energy consumption of industrial regions and reducing harmful emission considerably; secondly, it provides the possibility to utilise the industrial waste heat for energy needs of residential and commercial sectors that are a potential clients [24]. From the other side, it makes an appropriate background to implement an alternative energy sources including renewables that leads to additional reduction of energy prices and improves the environmental impact. The Total Site Analysis (TSA) is an approach that provides the utilisation of the waste industrial heat for different needs [25]. This direction is prioritised in different research labs due to wide application and a lot of approaches were developed last decade. Site energy improvements were proposed in Karimkashi S [26] that are based on the developments and modifications of the R-curve concept, which were previously developed by Kimura H and Zhu XX [27]. It was also used in [28] to estimate the investments of Total Site power cogeneration.

The authors in Nemet A, et al. [29] proposed using the intermediate utility loop to heat recovery of waste heat for energy needs inside the industrial clusters. This approach was later updated by Boldyryev S [30] and a methodology for minimisation of heat transfer area of steam boilers and condensers was provided. However, despite many successful industrial retrofit studies, there still remained several issues that remain unresolved and are of vital importance for the refineries, such as practical arrangements including plant layout, pressure drop, steam mains, number of steam boilers, steam traps etc. In this paper provides scientific approach and practical arrangements of retrofit of site utility system. There are recommendations for both engineers and plant managers to get technical details and decision making tools for economically viable retrofit of plant utility system.

Methods

It is possible to reduce the heat transfer area when implementing heat recovery of internal utility use. It was approved by Boldyryev S [30] and it depends on a certain temperature of intermediate utility loops. However, there are some technical issues of retrofit that contribute to capital investments such as numbers of heat transfer equipment as reported by Ahmad S, et al. [31], specific temperature difference, utility targets, recovery loops and energy prices [32]. Basically, the methodology grounded on basic principles of Pinch-point analysis [33] that is modified to use at Total Site level.

The developed approach consist of next stages: 1) Process Integration at individual units, energy targeting and utility requirements; 2) Total Site Profiles definition; 3) putting initial Total Site ΔT_{min}; 4) selection of enthalpy intervals, heat recovery and utility accounting all kinks of

Total Site Profiles; 5) putting of lower and upper bounds of intermediate utility loops for each enthalpy intervals; 6) calculation of heat transfer area of steam boilers and condensers in each enthalpy interval applying different temperature of steam mains; 7) optimising the level of steam mains determining minimum heat transfer of boilers and condensers; 8) calculation of numbers of boilers and condensers in all enthalpy intervals; 9) calculation of external utilities; 10) calculation of reduced investment and operation cost of retrofit; 11) applying previous steps for range of Total Site ΔT_{min}. The described procedure is illustrated in Figure 2.

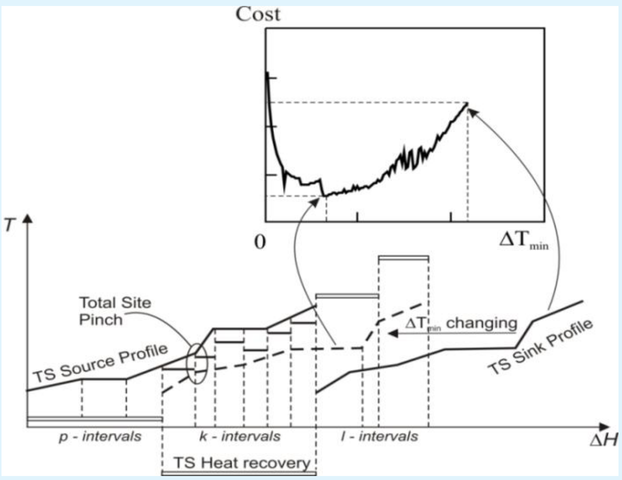

Figure 2: Total cost alternatives for Total Site heat integration (developed after [30]).

The heat transfer area of steam boilers and condensers for Total Site heat recovery loops and site utility units is calculated by (Equation 1):

$$A_{Total} = A_{TSHR} + A_{TSHU} + A_{TSCU} \quad (1)$$

The heat transfer area for hot and cold utility is calculated as reported in Smith R [33] selecting the utility temperature to minimise heat transfer area (Equation 2 and Equation 3).

$$A_{TSHU} = \sum_{i=1}^{l} \min_{t1<t_{HU}<t2} \frac{1}{\Delta T_{LM}^{C}} \left(\sum_{j=1}^{m} \frac{Q_j}{h_j} + \frac{Q_{HU}}{h_{HU}}\right)_i \quad (2)$$

$$A_{TSCU} = \sum_{j=1}^{p} \min_{t1<t_{CU}<t2} \frac{1}{\Delta T_{LM}^{C}} \left(\sum_{i=1}^{n} \frac{Q_i}{h_i} + \frac{Q_{CU}}{h_{CU}}\right)_j \quad (3)$$

Minimum heat transfer area on heat recovery loops is calculated by (Equation 4) that was previously modified in [**Error! Reference source not found.**]:

$$A_{TSHR} = \sum_{z=1}^{k} \min_{t1<t_{IM}<t2} \left(\frac{1}{\Delta T_{LM}^{H}} \left(\sum_{i=1}^{n} \frac{Q_i}{h_i} + \frac{Q_{IM}}{h_{IM}^{H}}\right) + \frac{1}{\Delta T_{LM}^{C}} \left(\sum_{j=1}^{m} \frac{Q_j}{h_j} + \frac{Q_{IM}}{h_{IM}^{C}}\right)\right)_z \quad (4)$$

The numbers of steam boilers, condensers and heat exchangers of external utility are calculated by Pinch-principles [33] assuming the number of units are the same as the number of streams in each enthalpy interval:

$$N_{HU} = \sum_{i=1}^{l} n_i^c,\ N_{CU} = \sum_{i=1}^{p} n_i^h \quad (5)$$

The number of heat exchangers of heat recovery loops is calculated from Sink and Source Profiles. There are arrays of heat boilers and condensers of intermediate utilities (Equation 6). It is based on the different intermediate utilities of recovery enthalpy intervals:

$$N_{HR} = \sum_{i=1}^{k} n_i^h + n_i^c \quad (6)$$

Total numbers of heat transfer units of site utility system are calculated from the Equation 7 and it is shown in Figure 3:

$$N_{Total} = N_{HR} + N_{HU} + N_{CU} \quad (7)$$

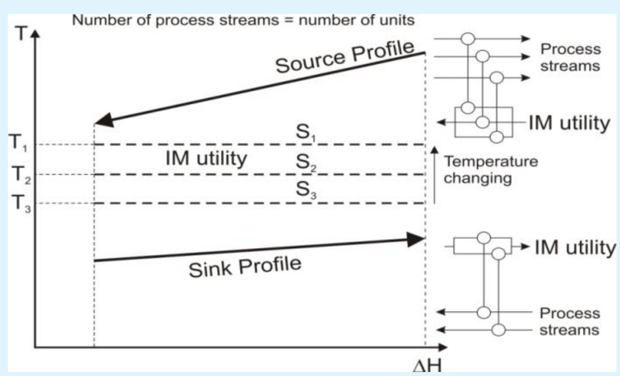

Figure 3: Streams and heat exchangers numbers for typical enthalpy interval of Total Site Profiles with use of intermediate utility (developed after [33]).

Energy demands are calculated of range of Total Site ΔT_{min} from Total Site profiles [25]. The fuel consumption of site utility system may be calculated from energy demand, ambient temperature, temperature of flue gases, and coefficient of excess air, furnaces and heaters efficiency. Cold utility consumption (e.g. cooling water, hot water, refrigerants etc.) is calculated based cold site energy targets, temperature differences and equipment efficiency.

The investment costs of Total Site heat recovery are calculated from heat transfer area (Equation 1), numbers of steam boilers and condensers (Equation 7) and equipment price.

The Refinary Case Study

The case study combined the stream data of 3 refinery units. These processes were integrated with use of Pinch-methodology. There are eight process streams available for Total Site integration and they are collected into the Table 1 with specific thermo-physical properties.

Stream	Type	TS (°C)	TT (°C)	CP (MW/°C)	ΔH (kW)	h (MW/(m² C))
Process A – 1 diesel	hot	100	60	0.05	2	0.0007
Process B – 1 feed gas mixture	hot	180	130	0.03	1.5	0.0001
Process C – 1 light fraction	hot	80	40	0.02	0.8	0.0005
Process D – 1 vacuum gasoil	hot	145	85	0.01	0.6	0.0006
Process A – 2 residue	cold	70	120	0.03	1.5	0.0005
Process B – 1 fuel oil	cold	100	140	0.04	1.6	0.0009
Process B – 2 product gas mixture	cold	150	240	0.02	1.8	0.0002
Process D – 2 fuel oil	cold	130	160	0.01	0.3	0.0007

Table 1: Stream data for Site Profiles

Site hot utility is a middle pressure steam with saturation temperature 25°C that is supplied by boiler house, cold utility is cooling water with temperatures range in summer 28 to 35°C and ambient air. Film heat transfer coefficients for hot and cold utilities are 0.001 and 0.0079 MW/(m² °C) respectively. The cost of hot utility is 366 EUR/kWy that corresponds to prices of natural gas in 2014 [34] and 10% conversion losses, the cost of cold utility is 36 EUR/kWy. The specific price of heat transfer area is taken of 800 Euro/m². It is a price of plate heat exchangers with high corrosion resistance. The coefficient of nonlinearity of heat transfer area price is 0.87. Installation costs including revamp of 1 steam boiler or condenser are 10,000 Euro. The calculation is made for 5 years plant life and return on investment employed of 10%.

The super targets of Total Site were built and shown in Figure 4. It is plotted with use of data from Table 1 varying the minimum temperature approach of Total Site Profiles and temperature of intermediate utilities of enthalpy intervals. Minimum total cost is identified of 2,107,800 EUR and it is found at Total Site temperature approach of 31°C (Figure 4a-c).

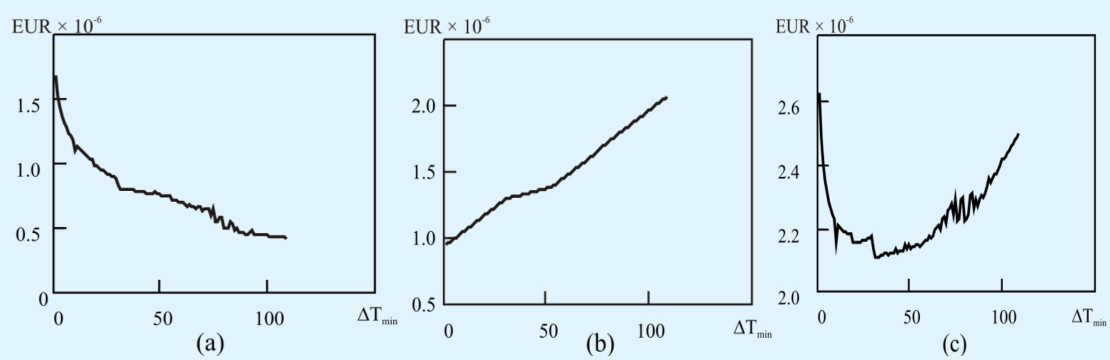

Figure 4: Total Site Cost Curves. (a) – reduced investments; (b) – reduced energy costs; (c) – reduced utility system costs.

The Total Site Profiles was built for optimal Total Site temperature approach and it is as shown in Figure 5. The overlapping part of Total Site Profiles is representing the heat recovery. Sink and Source profile temperatures limit the low and upper bound of temperature range of intermediate utility loop. The utility pinches appear between Site Profiles and utility loops as presented in Figure 5.

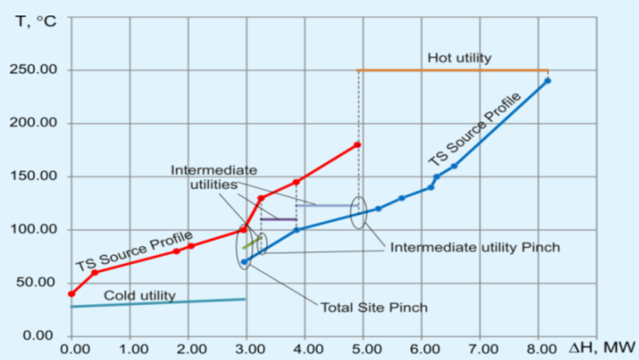

Figure 5: Total Site Profiles optimum temperature approach (Site ΔT_{min}=31°C).

The optimised utility system needs 2.96 MW (cooling water and air cooling) of the external cooling capacity while hot utility needs 3.26 MW of middle-pressure steam. There are several kinks on the Sink and Source Profiles at heat recovery. These breakpoints consist of three enthalpy intervals as shown in Figure 5 and Figure 3 intermediate utility loops are needed. The heat transfer area of steam boilers and condensers of each enthalpy interval is calculated by Equation (4) varying the temperature of intermediate utility from low to upper bound. Optimum levels of intermediate utilities were defined for each site temperature approach. The results of calculation of heat transfer area steam boilers and condensers of recovery system and steam mains are presented in Table 2.

The intermediate utility pinches are located at utility loops 1 and 3 and it is 8°C (Figure 5).

Enthalpy interval	ΔH, MW	TS, °C	TT, °C	ΔT_{min}, °C	hIM1, MW/(m2·°C)	hIM2, MW/(m2·°C)	S, m²	N_{HR}
#1	0.3	83	93	8	0.00011	0.00012	786.16	2
#2	0.6	110	110	10	0.008	0.0054	273.17	3
#3	1.05	123	123	8	0.0079	0.0053	408.87	3

Table 2: Calculation results of heat recovery loops.

The retrofit of refinery utility system described in this case study improves the heat recovery by 1.94 MW, wherein hot utility is lowered by 37.3%; cold utility is reduced by 39.6%. The representation of network structure of steam boilers and condensers is presented on Figure 6.

The realisation of retrofit of site utility system needs additional 1,468 m² of heat transfer area and 8 steam boilers and condensers. The annual energy saving of retrofitted utility system is 779,880 Euro and 777,474 Euro of capital investments are needed. The simple payback period of calculated case study is 11.96 month. Some economic results of presented case study are shown in Table 3.

	Hot utility (MW)	Cold utility (MW)	Recovery (MW)	Investment (EUR)	Saving (EUR/year)	Payback time (months)
Base case	5.2	4.9	0	–	–	–
Retrofit	3.26	2.96	1.94	777,474	779,880	11.96

Table 3: Economic results of utility system retrofit.

Discussion

The current paper provides the application of site recovery system; it shows the real case study and provides a decision making tool for the plant managers of retrofit of refinery utility system. However, there are some things are still needed deeper discussion and investigation.

The heat exchangers network for Total Site heat recovery consists of multiple steam boilers, condensers, water heaters and coolers. This equipment proposed to be placed at appropriate steam mains but there is a possibility for simplification of heat exchangers network and finding economic compromise between numbers of units, steam mains and heat transfer area. The number of heat exchangers and heat transfer area is higher comparison to individual processes due to heat transfer via intermediate utility loops. From the other hand the heat transfer coefficient of steam is much higher than of refinery process streams. In this case, the heat transfer area may be optimised with numbers of units, as mentioned above.

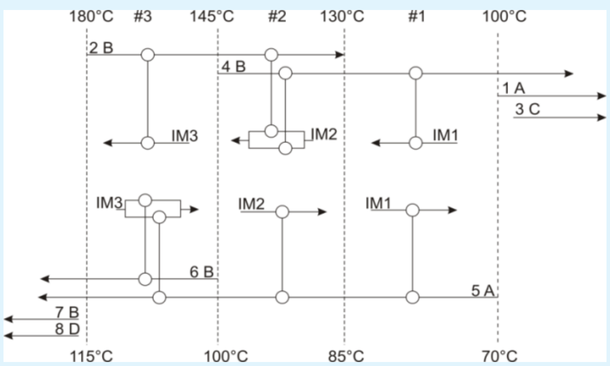

Figure 6: The network representation of steam boilers and condensers.

The trade-off of the heat recovery system is determined. Low price energy sources may move the retrofit project to the low heat recovery and bigger energy consumption. It decreases the realization time of retrofit project, which is very important for refinery operation schedule. The retrofit can be done during short time maintenance. The reduction of an energy prices may be done by renewables integration into site utility system but same measures have to be well analysed from scheduling point of view.

The additional analysis of site heat recovery systems should be delivered in the future work with the special attention to capital cost reduction by the selection of optimal level of intermediate utility loops and the simultaneous cogeneration opportunities. The design and revamp of site heat exchangers network deserves further attention. The summer operation mode should be analysed additionally because of heating and cooling demands will be changed and operation modes of boilers and condensers has to be adopted.

Conclusion

The presented paper minimises the retrofit cost of refinery utility system. It allows the practical recommendation of number of steam boilers and condensers as well as numbers steam mains, steam traps etc. The case study has shown a big potential of energy saving of refinery utility system. The use of excess heat provides a way to reduce the use of primary energy and to contribute to global CO_2 mitigation. The heating demands may be reduced by 37.3% and cooling demands by 39.6%; it is needed capital investments of 777,474 Euro and retrofit is payed back in 11.96 months. The result of this work may be used for practical recommendation of retrofit of site utility systems as well for design of energy systems of industrial regions.

Acknowledgments

The financial support by the EC and Croatian Ministry of Science Education and Sports project "CARBEN" (NEWFELPRO Grant Agreement No. 39).

Nomenclature

T	temperature, °C;
ΔH	enthalpy, kW;
A_{total}	total heat transfer area, m2;
A_{TSHR}	minimum heat transfer area of heat recovery, m2;
A_{TSHU}	minimum heat transfer area of steam boilers, m2;
A_{TSCU}	minimum heat transfer area of condensers, m2;
Δt_{min}	minimum temperature difference between two process streams, °C
ΔT_{min1}	minimum temperature difference of source side, °C
ΔT_{min2}	minimum temperature difference of sink side, °C
ΔT_{LM}^{H}	logarithmic temperature difference of source side, °C
ΔT_{LM}^{C}	logarithmic temperature difference of sink side, °C
t1	temperature low bound, °C;
t2	temperature upper bound, °C;
Q_i	heat of i hot stream, kW;
Q_j	heat of j cold stream, kW;
Q_{IM}	heat of intermediate utility of enthalpy interval, kW;
$Q_{RECOVERY}$	load of heat recovery, kW

Q_{HU}	heat of hot utility in enthalpy interval, kW;
Q_{CU}	heat of cold utility in enthalpy interval, kW;
Q_{Hmin}	hot utility target, kW;
Q_{Cmin}	cold utility target, kW;
h_i	film heat transfer coefficient of i process stream, W/(m2 °C);
h_j	film heat transfer coefficient of j process stream, W/(m2 °C);
h_{IM}^{C}	film heat transfer coefficient for condensation of intermediate utility, W/(m2 °C);
h_{IM}^{H}	film heat transfer coefficient for boiling of intermediate utility, W/(m2 °C);
h_{HU}	film heat transfer coefficient of hot utility, W/(m2 °C);
h_{CU}	film heat transfer coefficient of cold utility, W/(m2 °C);
h_{IM1}	film heat transfer coefficient of intermediate utility on source side, W/(m2 °C);
h_{IM2}	film heat transfer coefficient of intermediate utility on sink side, W/(m2 °C);
n	number of hot streams in enthalpy interval;
m	number of cold streams in enthalpy interval;
k	number of enthalpy intervals for heat recovery;
l	number of enthalpy intervals for hot utility;
p	number of enthalpy intervals for cold utility;
N_{HU}	number of heat exchangers for hot utility;
N_{CU}	number of heat exchangers for cold utility;
N_{HR}	number of heat exchangers for heat recovery;
N_{total}	total number of heat exchangers;
IM1	intermediate utility 1;
IM2	intermediate utility 2;
IM3	intermediate utility 3;
n_i^h	number hot streams in enthalpy interval;
n_i^c	number hot streams in enthalpy interval.

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