SELECTION OF UTILITY SYSTEM AND FUELS FOR EMISSION TARGETING OF CHEMICAL INDUSTRIES

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ABSTRACT
The present paper deals with CO_2 emission exiting from the chemical process industry which is responsible for global warming. The emission, released to environment, is minimized using different utility options and fuels. Further, the best option has been chosen based on emission generated and total cost involved for different utility systems. For this purpose, an example of aromatic plant has been considered for which steam turbine with natural gas is selected as best option. Further, the process is modified by incorporating the unutilized heat available with flue gas as well as condensate. This modification reduces the global emission by 9.2%. The present approach is applied to three different case studies and found that proper utilization of energy may reduce the emission up to 66.3%.

Key words: *Emissions targeting, Utility systems, Fuels, Total annual cost*

1. INTRODUCTION
Gaseous Emissions from industry adversely affect air quality and thus each country specifies limits to the amount of pollutants that can be released into the environment. The department of Energy, USA, highlighted that global CO_2 emissions are rising more than 2.7% per year [1] which is an alarming situation as it is responsible for global warming. These emissions originate either from process itself or utility system. Generally, following utility systems are considered: furnace, steam boilers, gas turbine and centralized power generation [2].

There is a consensus amongst environmental legislators that pollution prevention is an effective strategy for reducing environmental impact of industrial processes. This strategy was used by many researchers. It appears from the literature that Smith and Delaby [2] first reduced the flow rate of different flue gas pollutants by targeting it below allowable limit. They suggested that flue gas emissions could be reduced by changing fuel and utility system, improving heat recovery, etc. Further, Delaby and Smith [3] proposed an approach to compute minimum emission through fuel switching and modifying utility system.

Gadalla et al. [4] developed a model for computing CO_2 emission generated from heat integrated distillation column. Chaaban et al. [5] presented a method for selecting the best fuel. Mahmoud et al. [6] also used the fuel switching technique [2] and reduced the emission by 50%. Crilly and Zhelev [7] proposed guidelines of CO_2 emission targeting for an Irish electrical generation unit. These guidelines depend on forecasting and dynamic nature of supply-demand infrastructure. In contrast to these Dhole and Linnhoff [8] proposed a technique for emission targeting using total site targeting approach.

All the method discussed above use the minimum level of energy and correspondingly emission is computed. However, these methods do not include the total cost factor which is also an important aspect to consider. Thus, this paper presents a modified approach to select the best fuel as well as utility system for CO_2 emission based on total annual cost. Further, few modification in the process is also proposed that may reduce emission.

2. PROBLEM STATEMENT
A typical problem of the aromatics plant has been considered from open literature [2] for targeting flue gas emissions where four hot and five cold streams are available. For this plant stream data, utility data and different fuels are given in table 1, 2 and 3, respectively. It is assumed that the minimum temperature difference is 10^0C. The CO_2 emissions limit of 8000 kg/hr is imposed on this plant where a typical electricity generation cycle (steam turbine plant) is used with no gaseous pollution abatement technology as a basis. Its overall efficiency is 28% (including distribution). The pinch analysis shows that the hot and cold utility requirements are 17.28 MW and 18.5 MW, respectively. These informations are used as a base case for comparison.

Table 1. Stream data for an aromatics process

Streams	CP (kW ◦C^{-1})	Supply temp. (◦C)	Target temp. (◦C)
1	160	220	160
2	60	220	60
3	400	160	60
4	100	327	45
5	100	100	300
6	70	35	164
7	350	85	138
8	60	60	170
9	200	140	300

Table 2. Utility data

Utility	Property	Temperature (^{0}C)
Steam	HP (saturated, 48.8 bar)	298
Furnace flue gas	T_{Flame}	1800
	T_{Stack}	160
Gas turbine	T_{In}	1027
	T_{Out}	720
	T_{Stack}	160

Table 3. Alternative fuels (ultimate analysis in mass %)

Component	Natural gas	Diesel oil	Coal
Carbon	75.38	86.2	74.5
Hydrogen	23.4	12.39	4.5
Sulphur	0.1	0.39	2.0
Water	0	0.33	8.0
Ash	0	0.3	8.0
Nitrogen	1.12	0.195	1.0
Oxygen	0	0.195	2.0
NHV (kJ kg-1)	5.16×10^4	4.2×10^4	3.0×10^4
Cost ($/GJ)	4.21	7.79	1.61

3. METHODOLOGY

The present paper considers only the CO_2 emission. The rate of emission is computed using Eq. 1 [2].

$$CO_2\ flowrate = \frac{Q_{FUEL}}{NHV} \times \frac{C\%}{100} \times \alpha \tag{1}$$

Where, Q_{FUEL} = heat duty from fuel burnt (kg hr^{-1})
NHV = fuel net heating value (kJ kg^{-1})
C% =mass percentage of carbon in fuel
α = ratio of carbon dioxide and carbon molar mass

3.1. Selection of Best Fuel and Utility System

In the present study three fuels such as natural gas, diesel oil and coal are considered as these are extensively used for combustion process. For the selection of best fuel it is assumed that combustion is taking place in furnace where these fuels are burnt one at a time. The CO_2 emissions produced for each case are plotted in figure 1. It shows that emissions are below the allowable limit of 8000 kg/hr. Moreover, emission may reduce by 28.8% and 41.2% when the fuels are switched to natural gas from oil and coal. This is due to relatively low carbon content and high NHV of gaseous fuel. Thus, natural gas is selected as best fuel amongst three.

For the selection of best utility system amongst furnace, steam turbine and gas turbine natural gas is considered as a fuel. The models of these units, used in the present work, are considered from the work of Smith and Delaby [2]. The CO_2 emissions generated from three utility systems for production of 17.28 MW of heat are plotted in figure 2.

From this figure it is concluded that on a local basis, a furnace has lowest emissions than steam turbine and gas turbine.

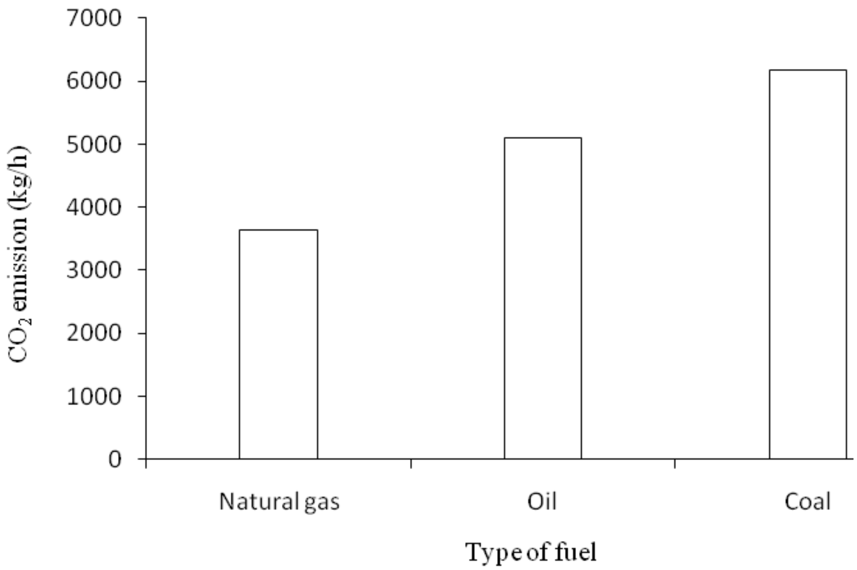

Figure 1. CO_2 emission generated from furnace using different fuels

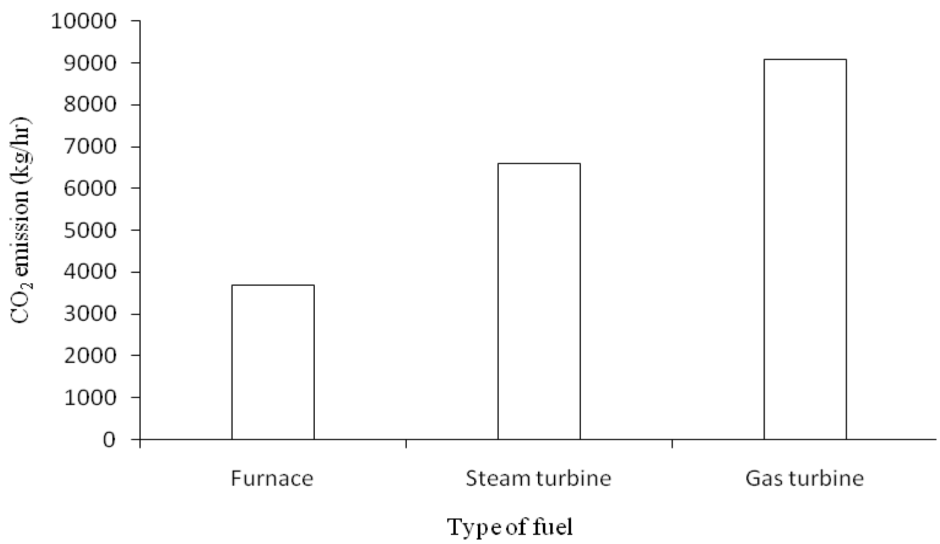

Figure 2. CO_2 emission generated from different systems using natural gas as a fuel

Gas and steam turbines are used to generate power which may export. Consequently, emission related to power is also considered at exported site. Thus, in such cases global emission is computed using following definition:
Global emissions = [local emissions] + [emissions relating to power imported from central station] – [emissions relating to power exported from site]

The local as well as global emissions are equal for furnace. However, in the case of steam turbine 1929.4 kg/hr of CO_2 emission is related to power exported from site, hence, the global emission from steam turbine is only 2063.9 kg/hr. Similarly, the global emission from gas turbine is 1324.9 kg/hr. It should be noted that emissions are well below the allowable limit of 8000 kg/hr and gas turbine produces least emission than steam turbine and furnace. Furnace, gas turbine and steam turbine deliver 0, 2.79MW and 6.0MW of power, respectively, to the central power station. Henceforth, these data are referred as a base case.

3.2. Cost of HEN and Utility System

The gas turbine produces less emission than furnace and steam turbine for same fuel. It is not adequate basis for comparison. The cost analysis is further required to find optimum system. For this purpose, capital and operating costs of heat exchanger network (HEN) as well as utility system are considered.

Total annual cost (TAC)=Annualized Operating cost (OC)+Annualized Capital cost (CC)

Where,

CC = Capital cost of utility system + Capital cost of HEN

And OC = Fuel cost + Cold water cost

The capital cost of furnace with diesel oil is considered as \$34681.2/year [9]. The targeted capital cost for HEN using the stream data shown in table 1 is \$1.13*10^6/yr. This cost is computed using HEN life and rate of interest as 5 years and 10%, respectively.

CC = 34681.12 + 1.13*10^6 = 1164682

The operating costs of diesel oil and cold water for the case of furnace are computed as:

OC = 11915584.8 + 185000 = 12100584.8

Therefore, TAC for furnace with diesel oil is predicted as \$ 13265266.8/yr. Similarly, costs for other systems are computed. The complete TAC is summarized in table 4 which shows that capital cost of gas turbine is considerably higher than that of furnace and steam turbine. Thus, gas turbine can not be selected as optimum system though it produces less emission.

Table 4. Cost analysis for different utility system

System	Capital cost (\$/year)	Operating cost (\$/year)			Total annual cost (\$/year)		
		Diesel oil + cold water	Coal + cold water	Natural Gas + cold water	Diesel oil + System	Coal + System	Natural gas + System
Furnace + HEN	1164682	12100584.8	2647653.2	7129380.8	13265266.8	3812335.2	8294062.8
Steam turbine +HEN	2004632.5	14441270	3131417.6	8493532.4	16445902.5	5136050.1	10498164.9
Gas turbine + HEN	3379055	30643694	6480060.8	17936274.8	34022749	9859115.8	21315329.8

Based on TAC furnace is found as best utility system, however, it gives 43% and 63.5% higher emission than steam turbine and gas turbine, respectively. Thus, the best system is steam turbine using coal as it produces 43% less emission with 26% more expense in comparison to furnace. If natural gas is selected in the above system then it produces 70% less emission with 46% higher TAC than the case of coal.

3.3. Modification in the Process

The heat generated in the utility system such as furnace, gas turbine and steam turbine is utilized up to a fixed level. For example flue gas, produced in furnace, is used to heat the process up to stack temperature of 160^{0}C. After that it remains unutilized and is released to atmosphere. Similarly, the cases are with gas and steam turbine. Therefore, the extra heat available with flue gas as well as condensate can be utilized in the process. For this purpose these streams are considered as hot streams in the process. The heat capacity flow rate, CP, of each stream may be calculated as shown below for the case of furnace:

17280 = CP (1800-160)

CP = 10.53 kW/^{0}C

These hot streams are detailed in table 5. These are used along with stream data, shown in table 1, and consequently three modified cases are formed, Case 1: furnace exit and stream data of table 1, Case 2: gas turbine exit and stream data of table 1 and Case 3: steam turbine exit and stream data of table 1. The hot and cold utilities are computed for each case and compared based on total operating cost. The comparison is presented in table 6 which shows that Case 3 gives the least operating cost. For calculation of operating cost, the costs of steam and cold water are considered as \$120/kW/yr and \$10/kW/yr, respectively. The global emission for case 3 is 9.2% less than the base case as shown in table 7. This is because for the Case 3 hot utility consumption is less than the base case. Thus less fuel is required which causes less emission.

Table 5. Details of exits of furnace and gas and steam turbines

Stream	Supply temp. (^{0}C)	Target temp. (^{0}C)	CP (kW/^{0}C)
Furnace	160	25	10.53
Gas turbine	160	25	30.86
Steam	298	25	11.50

Table 6. Utilities and operating costs for different cases

Problem	Hot Utility(KW)	Cold Utility(KW)	Operating Cost ($/year)
Base case	17280	18500	2258600
Case 1	17280	19922.9	2272829
Case 2	17280	22664.8	2300248
Case 3	15693	20052.5	2083685

Table 7. Comparison between Base case and Case 3

Particular	Base case	Case 3	Reduced (%)
Hot utility, kW	17280	15693	9.2
Global Emission	3872.70	3517.03	9.2
Operating cost ($/year)	2258600	2083685	7.7

In fact, when condensate of steam turbine cools down from 298 to 25 ^{0}C, it enters the boiler at 25 ^{0}C and requires to be heated up to 298 ^{0}C. Thus, extra fuel is to be burnt for this purpose. The operating cost in this case also includes the cost of extra fuel and thus total operating cost for Case 3 is $2103737.5/year.

3.4. Computation of Optimum ΔT_{min}

For the base case ΔT_{min} equal to 10 ^{0}C is considered arbitrarily. It is an important variable for design of HEN as it considerably influences the total annual cost (TAC). With the increase in the value of ΔT_{min} the required hot and cold utilities are increased to give an increase in OC whereas CC decreases due to the increase in the driving force for heat transfer between hot and cold composite curves. The problem is a perfect case for optimization and thus calls for the determination of optimum value of ΔT_{min}, which will provide lowest TAC. Therefore, while searching for an optimum value of ΔT_{min} its numerical value is varied from 7 to 27 in discrete steps and TAC is retargeted based on the procedure discussed above. The optimization curve is shown in figure 3 which indicates that minimum value of TAC corresponds to a value of ΔT_{min} □ equal to 17^{0}C, which is obviously the optimum ΔT_{min}. Figure 3 also shows the global emission at different ΔT_{min} which is generated from steam turbine using natural gas as a fuel. This information indicates that for ΔT_{min} equal to 17 though the hot utility is increased by 17% the emissions are still below the allowable limit of 8000 kg/hr. For this optimum case the total annual cost of HEN and steam turbine is decreased by 7.74 % than the base case. Thus, the plant can effectively be operated at optimum ΔT_{min}.

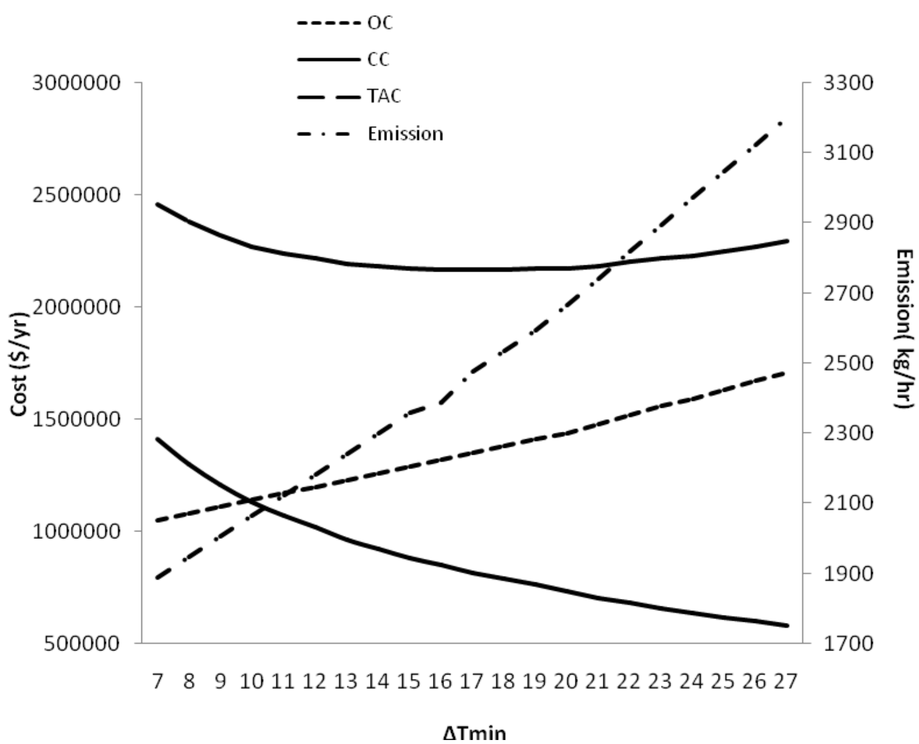

Figure 3. Cost and emissions for different utilities for different ΔT_{min}

4. RESULTS AND DISCUSSION

To apply the present technique three case studies are considered in which first the HEN and utility system is optimized based on TAC and then CO_2 emission is computed. The steam turbine is used as a utility system with natural gas as a fuel. The main purpose of the computing optimum TAC explained as: the cost of natural gas is appreciably higher and it may be compensated when the optimum case of HEN i.e. HEN with minimum TAC is considered for computing emission. However, it is acceptable only when the emission is below the allowable limit of the plant.

4.1. Case Study-1

The presents HEN problem is taken from open literature [10]. The stream data is provided in table 8. The minimum temperature difference (ΔT_{min}) of 20 °C is used as an initial guess. The saturated steam is available at 205°C (1718 kPa). For the steam data shown in table 8 the CO_2 emission from steam turbine using natural gas is found as 192.94 kg/h. However, for optimum value of ΔT_{min} equal to 13°C the CO_2 emission is 95.15 kg/h which is 50 % less than the previous case. If condensate of steam is used as a hot stream then process hot utility requirement is negligible. Thus in this case no steam is to be generated. Consequently no emission will be produced from utility system.

Table 8. The Stream data for the Case study 1

Stream (s)	T^s (°C)	T^t (°C)	CP (kW/ °C)
Hot	175	45	10
Cold	20	155	20
Hot	125	65	40
Cold	40	112	15

4.2. Case Study-2

Mahmoud et al. [6] considers a pre-heat train of a crude distillation unit. The stream and cost data for the process are shown in table 9 with ΔT_{min} as 10°C and corresponds to it hot utility is 80418 kW. The CO_2 emission generated by furnace using natural gas is equal to 17000 kg/h. The saturated steam is available at 298°C. For this stream data the emission of plant was reduced by 50% [6].

Table 9. Stream and cost data for the Case study 2

Stream (s)	Flow (kg/s)	T^s (°C)	T^t (°C)	h (W/m^2°C)
H1	23	180	30	492.2
H2	44	270	40	477.8
H3	13	350	30	439.8
H4	56	380	50	470.7
H5	253	150	100	561.5
H6	148	290	190	432.6
C1	200	20	390	343.0

The authors claimed reduction in energy by 26%. However, in the present work energy saving of 47% is predicted at optimum ΔT_{min} equal to 11°C. This value is obtained using the costs reported in the work of Mahmoud et al. [6]. For the predicted energy consumption emission is found as 8219.82 kg/h using natural gas. Moreover, if steam turbine is used in place of furnace then emission is further reduced to 5746.20 kg/h. Therefore, total reduction in emission is predicted as 66.19% where 51.64% is due to the energy saving and 14.55% is because of employing steam turbine as a utility system. If the condensate steam use as stream then the required heat is further reduced by 0.2%. Thus in this case emission is reduced upto 66.3%.

4.3. Case Study-3

A septuple effect flat falling film evaporator system, being operated in a nearby Indian paper mill for concentrating weak black liquor, is considered to reduce the emission as shown in figure 4. The measured value of steam consumption for the system is 8800 kg/h (140°C) which corresponds to 6540.504 kW of hot utility. At this value emission is computed using steam turbine with natural gas and found as 1728.74 kg/h. Further, the steam consumption is reduced to 7895 kg/h by induction of liquor heating with condensate, feed, product and condensate flashing [11]. Thus, the energy saving of 10.3% reduces the emission by 10.28 %.

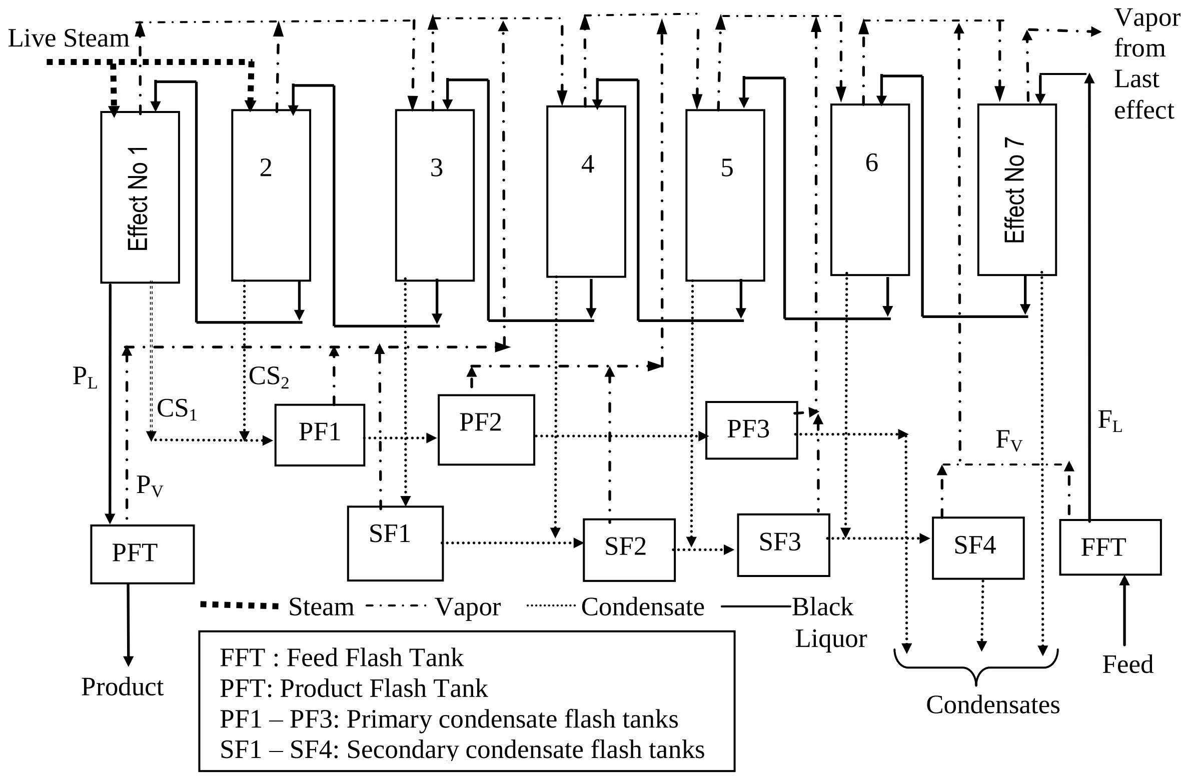

Figure 4. Schematic diagram of a septuple system with flashing

5. CONCLUSIONS

The salient conclusions of the present work are as follows:

1. Natural gas produces least emission. In the present work, first the problem is optimized based on TAC and then emission is computed using natural gas.
2. Gas turbine generates less global emission however the capital cost of it is very high. Therefore, steam turbine is selected as less emission producing as well as cost effective utility system.
3. The results of three case studies show that proper utilization of energy may reduce the emission up to 66.3%.
4. The system is modified by incorporating the unutilized heat available with flue gas as well as condensate. This modification reduces the global emission and operating cost by 9.2% and 7.7%, respectively.
5. The supertargeting of a process gives optimum value of ΔT_{min} for which local and global emissions are computed. It shows that though the hot utility is increased emissions are considerably below the imposed limit. Thus, the plant can be effectively operated at optimum ΔT_{min}.

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