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# EMISSIONS REDUCTION OF A CHEMICAL PROCESS PLANT BY MAXIMIZING ENERGY RECOVERY, MINIMIZING ENERGY LOSSES AND FUEL SWITCHING

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## ABSTRACT

### Article History

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### Keywords

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Fuel switching

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Increasing population and technology progress required more energy consumption and more fuel combustion. The major source of pollution is harmful gasses emission due to fossil fuel combustion. In this work, we chose a chemical process as a case study for gasses emission reduction through the application of energy management methodology including four techniques. Firstly, maximizing of energy recovery realized by designing a heat exchangers network (HEN) where the rate of energy saving and so on emission reduction reached to 60% compared to the existing case. Secondly, minimizing of heat losses by using optimum pipes insulation where reduction of fuel consumption reached to 15%-20% and it is directly reduced gasses emission by the same percentage. Thirdly, fuel switching from fuel oil to natural gas reduced gasses emission by 44% compared to the existing case. The fourth one, integration between the last three techniques can guarantee a reduction of harmful gasses emission by 80% compared to existing unit conditions.

**Contribution/Originality:** This study originates a new formula of energy management methodology to reduce harmful emissions. The paper's contribution is integration between HEN deigning, insulations and fuel switching. This study is one of few studies which can be applied for any process.

## 1. INTRODUCTION

Climate change, global warming and greenhouse effect are direct results of fuel combustion emissions. All industrial countries introduced energy KYOTO protocol through periodical meeting under united nation supervision. The goal of this protocol is obeying and applying emission control regulations. Energy management can save money and in parallel protect the environment by minimizing emissions. Heat exchanger network (HEN) is an important technique for maximizing heat recovery in the industrial chemical process and reducing external heating and cooling utilities [1]. Many searches have been published to improve HENs design and synthesis along the last 40 years [2]. Pinch technology technique is a thermodynamic method used to design (HEN) with the optimal condition to integrate and minimize utilities [3-7]. Mathematical formulation through linear, non-linear and mixed integer linear programming is another method has been applied by several researchers to synthesis the optimum flexible HEN [8-11].

For any chemical unite, the simplest way to minimize energy losses is the insulation application [12].

While insulation of any unite reduces the energy requirement and so on reduces gasses emission added capital cost is required.

Economic balance for any insulation application between energy losses control and added cost took place to define optimum insulation thickness. Definition the suitable insulation with the optimum thickness depends on pipe material, fuel type and operating temperature range.

The pollutants accompanying to fuel combustion differ according to physical properties of the fuel. So, emissions can be controlled by fuel switching and using less emitter fuel [13, 14].

In this work, the target is minimizing the emissions of a case study through the application of energy management methodology which including four techniques. Firstly, is energy recovery by designing of Heat Exchanger Network (HEN) where 66% reduction of both energy used and combustion' emission achieved. Secondly, is minimizing heat losses by application of optimum insulation thickness where fuel consumption and emission reduced by 15%. Thirdly, Fuel switching by replacement fuel oil with natural gas to reduce emissions by 44% compared to the existing case. The fourth one is the integration between the 3 techniques; where maximum energy recovery achieved through the revamped unite, using optimum thickness insulation and using natural gas as instead fuel. This integration achieved the highest percentage of emission reduction reach to 80%.

## 2. CO<sub>2</sub> EMISSIONS

The rate of air pollutants increased parallel to technology progress which required more of energy consumption.

**While CO<sub>2</sub> emissions are responsible for climate change and global warming, it has other dangerous effects as:**

- Dangerous effect on human health especially respiratory system, asthma, bronchitis, lung cancer, and heart disease sometimes leads to death
- Disturbance of environmental balance as:
  1. Shortage of some soil mineral components as Zinc and iron which will cause malnutrition and health weakness in the future.
  2. Increase the salinity ratio of seas and oceans which will cause disturbance of marine organisms' cycle and coast damage.

Industrial sector and power generating stations are the causatives of 82% of CO<sub>2</sub> emissions compared to other sectors as shown in Figure 1. Research statistics confirm that fossil fuel consumption is still the highest rate until 2030 compared with other fuel types. As shown in Figure 2 CO<sub>2</sub> emission represents around 76% of fossil fuel combustion, so CO<sub>2</sub> emission detecting and control is environmentally effective for the industrial sector. Equations used for emission calculations of fuel combustion are listed below [13-16]. As shown in Equation 3 rate of pollutants emissions depends on fuel load  $Q_{fuel}$  and fuel properties.  $Q_{fuel}$  can be estimated through Equations 1, 2

$$\eta_{furnace} = \frac{T_{TFT} - T_{STACK}}{T_{TFT} - T_o} \quad (1)$$

$$Q_{fuel} = Q_{proc.} / \eta_{furnace} \quad (2)$$

$$M_{pol} = Q_{fuel} * \beta * \Phi / NHV \quad (3)$$

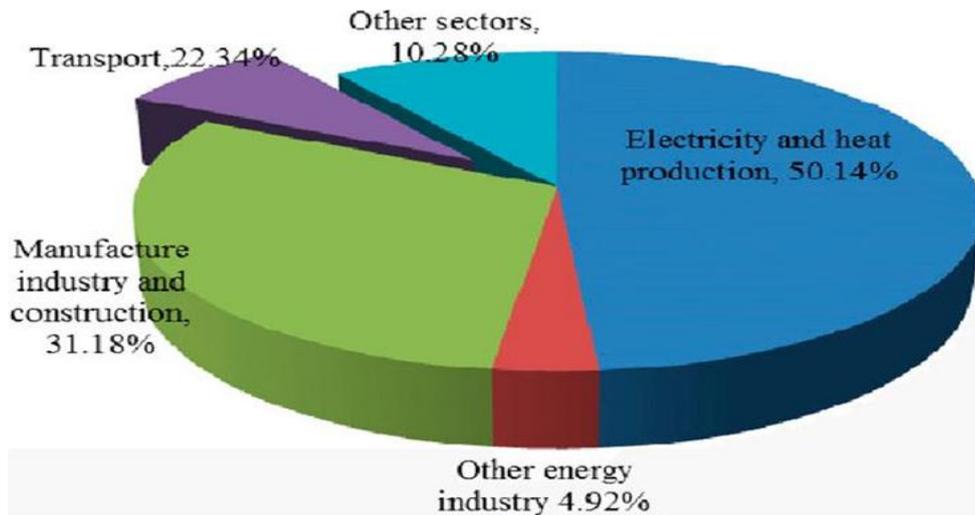


Figure-1. %CO<sub>2</sub> Emissions of Different Sectors [15].

Source: U.S. Environmental Protection Agency (EPA), Inventory of U.S. Greenhouse Gas Emissions and Sinks: April 2018.

U.S. greenhouse gas emissions by gas, 2016<sup>1</sup>  
Total = 6,511 million metric tons of carbon dioxide equivalent (CO<sub>2</sub>e)

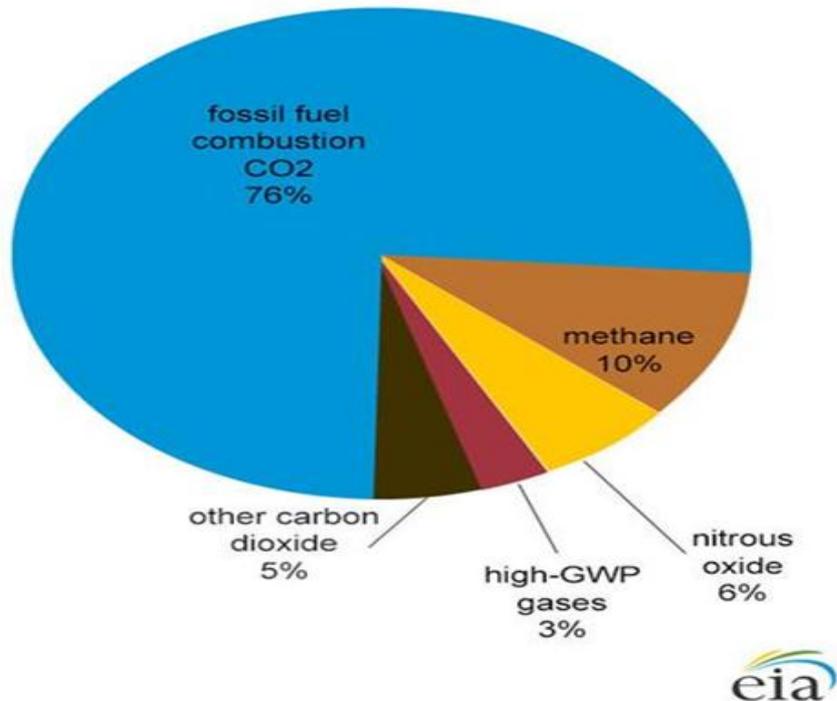


Figure-2.% of Fossil Fuel Combustion Components [16].

Note: CO<sub>2</sub>e based on 100-year global warming potential.

Source: U.S. Environmental Protection Agency (EPA), Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2016, April 2018.

### 3. ENERGY MANAGEMENT METHODOLOGY FOR REDUCING CO<sub>2</sub> EMISSIONS

The pivot of this methodology is reducing CO<sub>2</sub> emissions through maximizing energy recovery, minimizing heat losses and fuel switching.

The methodology consists of four techniques:

#### 3.1. Firstly, Energy Recovery through Heat Exchanger Network (HEN)

Pinch technology technique is an effective method for maximizing the process of energy management through designing HEN; it depends on the exchange between energy sources and energy sinks of the process. Where, after

classification the process into streams with its thermal and physical properties, estimation of minimum utilities and defining pinch point take place. Many alternatives HEN designs are realized by using pinch instructions: [1, 3, 4].

1. Do not transfer heat across the pinch point.
2. Do not use hot utility below the pinch point.
3. Do not use cold utility above the pinch point.
4. Begin with pinch match and move away.
5. Pinch matches obey this rule:
  - $CP_{hot} \leq CP_{cold}$  (above pinch)
  - $CP_{hot} \geq CP_{cold}$  (below pinch)

Economic evaluation, operability and flexibility help the designer to choose the optimum HEN achieving minimum external heating and cooling with the least cost.

### 3.1.1. HEN Cost Estimation

The overall cost of HEN is detected using Equation 4 which consists of capital and operating cost. Annualized Operating cost (OC) includes utility cost as fuel and water see Equation 5. Unit capital cost is a function of heat transfer area and can be calculated using Equations 7,8,9. Summation of units' cost introduces Annualized Capital Cost (CC) see Equation 6 [6, 7].

$$\text{Overall Annual Cost} = \text{Annualized Operating Cost (OC)} + \text{Annualized Capital Cost (CC)} \quad (4)$$

$$\text{Annualized Operating Cost (OC)} = \text{Fuel cost} + \text{Cold Water Cost} \quad (5)$$

$$\text{Annualized Capital Cost (CC)} = \text{Capital Cost of HEN} \quad (6)$$

$$\text{Unit Capital Cost (\$)} = 8600 + 670(\text{area})^{0.83} \quad (7)$$

$$\text{Area} = Q / U * \Delta T_{lm} \quad (8)$$

$$1 / U_{ij} = 1/h_i + 1/h_j \quad (9)$$

Life time = 5 years

No. of working days/y = 330

### 3.1.2. Minimum Number of Units

The capital cost of HEN affected by the number of units and the minimum number of units for any HEN can be estimated by Equation 10: [5-7].

$$N_{min} = N_h + N_c + N_u - 1 \quad (10)$$

**Where:**

$N_{min}$  : Minimum Number of Units

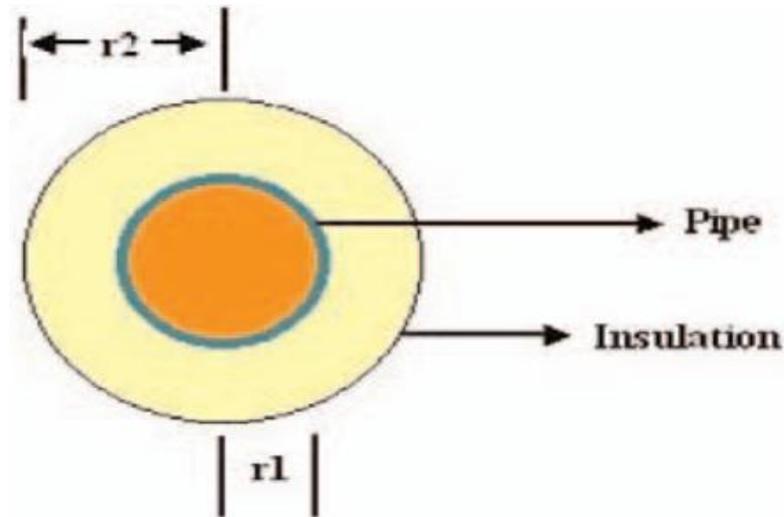
$N_h$  : Number of hot streams

$N_c$  : Number of cold streams

$N_u$  : Number of utilities

### 3.2. Secondly, Application of Thermal Insulation

A thermal insulator is a weak conductor of heat which has low thermal conductivity. Insulation is used in many sectors and has a good effect on industrial processes to prevent heat loss or heat gain, see Figure 3. Minimization of heat loss through insulation has an economic benefit, although it facilitates the unite process control and guarantees the operators protection. The insulator has an extra role which is a fire protection and corrosion inhibitor [12, 17].



**Figure-3.** Cross section of a pipe with radius  $r_1$  before insulation &  $r_2$  after insulation.  
 Source: [www.seav.vic.gov.au/ftp/advice/business/info\\_sheets/EnergySaving-Insulation.pdf](http://www.seav.vic.gov.au/ftp/advice/business/info_sheets/EnergySaving-Insulation.pdf) [www.pera.org](http://www.pera.org)

### 3.2.1. Types of Insulation

Insulation selectivity depends on the process operating conditions and pipes material. The effect of insulation in the case of copper and steel pipes is more obvious than plastic pipes case in reducing energy losses. Insulations are classified into two groups:

#### 3.2.1.1. According to Temperatures Range

##### *Low-Temperature Insulations (up to 90 °C)*

This type is suitable for refrigerators, cold and hot water systems, storage tanks. The materials of Cork, Wood, Mineral Fibers, Polyurethane and expanded Polystyrene are a candidate for this insulation.

##### *Medium Temperature Insulations (90 – 325 °C)*

This type of Insulators is used in low-temperature heating and steam production equipment, steam lines. The materials used in this temperatures range to include 85% of (Magnesia, Asbestos, Calcium Silicate and Mineral Fibers).

##### *High-Temperature Insulations (over 325 °C)*

This type of insulators is used for high-temperature applications as super heated steam system, oven dryer and furnaces. The suitable materials for this range are Asbestos, Calcium Silicate, Mineral Fibers, Mica and Vermiculite based insulation, Fireclay or Silica-based insulation and Ceramic Fibers.

#### 3.2.1.2. According to Fabrication Materials

Insulation materials can also be classified into organic and inorganic types.

##### *Organic Insulations*

AS Poly urethane form and Thermocol which are based on hydrocarbon polymers.

##### *Inorganic Insulations*

This is based on Siliceous/Aluminous/Calcium materials. The forms of this insulator are fibrous, granular or powder so they are used in a wide range. Mineral wool, Calcium silicate and Thermocol are examples of inorganic insulation. They are suitable for industrial process plant piping, heating and chilling system pipelines.

### 3.2.2. Optimum Thickness of Insulation

While insulation application reduces heat losses, it required an added capital cost. The insulation thickness ( $t_k$ ) is an effective factor, whereas the thickness increases the surface temperature ( $T_s$ ) decreases and so on the heat losses ( $S$ ) decrease. On the other hand, increasing the insulation thickness required more cost see [Figure 3](#). Definition of optimum insulation thickness takes place through the economic balance between fuel cost saving and insulation cost. Where insulation cost can be estimated using [Equations 11-15](#) and cost of fuel loss can be estimated using [Equations 16, 17](#).

$$S = [10 + (T_s - T_a)/20] * (T_s - T_a) \quad (11)$$

$$H_s = S * A \quad (12)$$

$$\text{Insulation Cost} = V * \rho * C_{\text{ins}} \quad (13)$$

$$V = \pi * (r_2^2 - r_1^2) * L \quad (14)$$

$$t_k = r_2 - r_1 \quad (15)$$

$$H_f = [H_s * \text{Yearly hours of operation}] / [\text{NHV} * \eta_b] \quad (16)$$

$$\text{Annual cost of fuel loss} = H_f * C_f \quad (17)$$

### 3.3. Thirdly, Fuel Switching

While natural gas is a fossil fuel, global warming emissions from its combustion are much lower than those from coal or oil. Natural gas emits 50 to 60 percent less carbon dioxide ( $\text{CO}_2$ ) when combusted in a chemical process or power plant compared with emissions from oil and coal [\[18, 19\]](#). As emissions decreased many health problems like asthma, bronchitis, lung cancer, and heart disease controlled. The recent promising discoveries of natural gas fields as Mediterranean fields facilitate fuel switching technique with the least added operating cost.

Fuel switching (replacement types of fuels with natural gas) realized great results in  $\text{CO}_2$  reduction which has a positive impact on the environment, especially in the industrial sector [\[20\]](#).

The properties of different types of fuel are listed in [Table 1](#) where it is obvious that natural gas has the highest net heating value, least price with least emissions.

**Table-1.** Comparison between types of Fuels according to their components and properties [\[20\]](#).

Fuel Type \ Component	Natural Gas	Diesel Oil	Fuel Oil	Coal
Carbon	75.4	86.2	87.24	74.5
Hydrogen	23.4	12.39	10.94	4.5
Sulphur	0.1	0.39	0.74	2.0
Water	0	0.33	0.1	8.0
Ash	0	0.3	0.1	8.0
Nitrogen	1.12	0.195	0.24	1.0
Oxygen	0	0.195	0.64	2.0
Price	0.4453 \$/m <sup>3</sup>	7.79 \$/GJ	0.7935 \$/kg	0.3129 \$/kg

Source: National Energy Technology Laboratory (NETL) [\[18\]](#)

### 3.4. Fourthly, Integration between the Three Techniques

Application the last three techniques separately, gives many options for emission reduction. Operability, process control and cost estimation are factors help search team of any unit to choose the suitable one.

#### 4. RESULTS & DISCUSSION

##### Application of Energy Management Methodology on a Case Study

The plant flowsheet of the case study is shown in Figure 4, where the feed stream firstly passes through the heater to reach to the reaction temperature and the reactor effluent is further heated, and the products are separated in a distillation column. The reboiler and condenser use external utilities for control purposes. The overhead and bottoms products are cooled and sent for further processing. The grid diagram of the process is shown in Figure 5. The actual utilities' consumption are as heating load of 14000 kW and cooling load of 13800 kW. Energy management methodology including four techniques has applied on the case study:

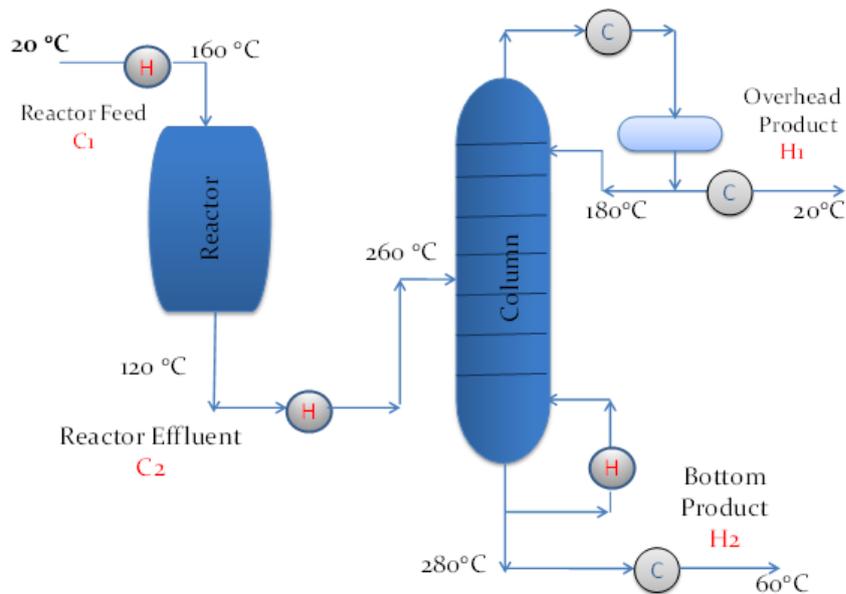


Figure-4. A Typical Plant Flowsheet of the Case Study.

Source: Gabr [1].

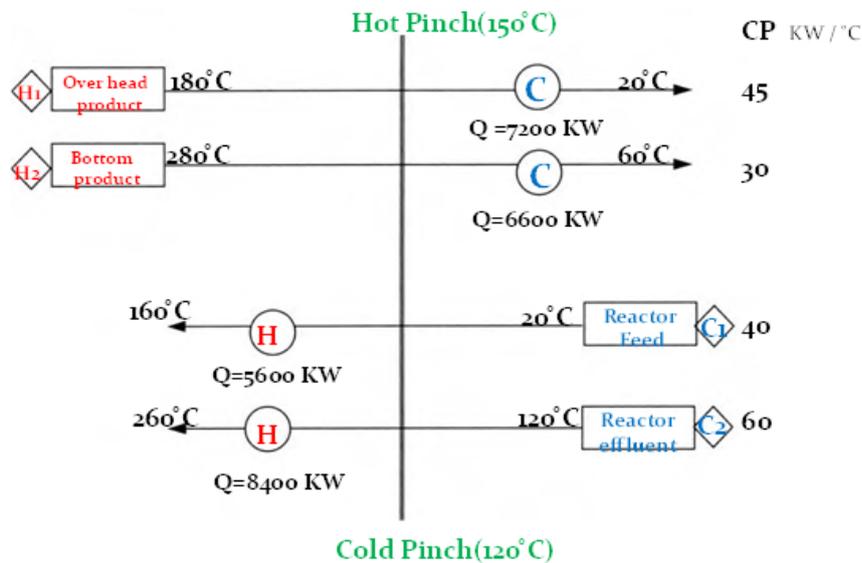


Figure-5. Grid Diagram of the existing Flowsheet

Source: Gabr [1].

##### 4.1. First Technique; Reducing of Emissions through Energy Recovery of the Case Study by HEN Designing

- As a beginning step, classification the process into hot, cold streams and utilities took place. See Table 2.
- Application of Pinch rules to define pinch point and estimate minimum energy consumption took place, where  $[Q_{Hmin} = 4750 \text{ kW}, Q_{Cmin} = 4550 \text{ kW}, T_{hp} = 150 \text{ °C}$  and  $T_{cp} = 120 \text{ °C}]$

- Many alternative HEN designs are available, but the design with least alterations compared to existing grid diagram is shown in Figure 6.A, where (loop presented as dashed lines). Minimization number of units by breaking loop to minimize capital cost took place; see Figure 6.B which is a candidate for revamping.
- The Flowsheet of the case study after revamping is shown in Figure 7, where the added two heat exchangers are presented in yellow color.
- The revamped design consumed utility less than the existing case by around 66% and represented in net annual saving reached to 1,400,00 \$. As a parallel result to minimize energy consumed, the CO<sub>2</sub> emission reduced by 66% which has a good effective environment impact.

Table-2. Streams' data of the Case study.

Stream №	Stream Name	T <sub>in</sub>	T <sub>out</sub>	C <sub>p</sub> kW/°C
C1	Reactor Feed	20	160	40
C2	Reactor Effluent	120	260	60
H1	Overhead product	180	20	45
H2	Bottom Product	280	60	30

Source: Gabr [1].

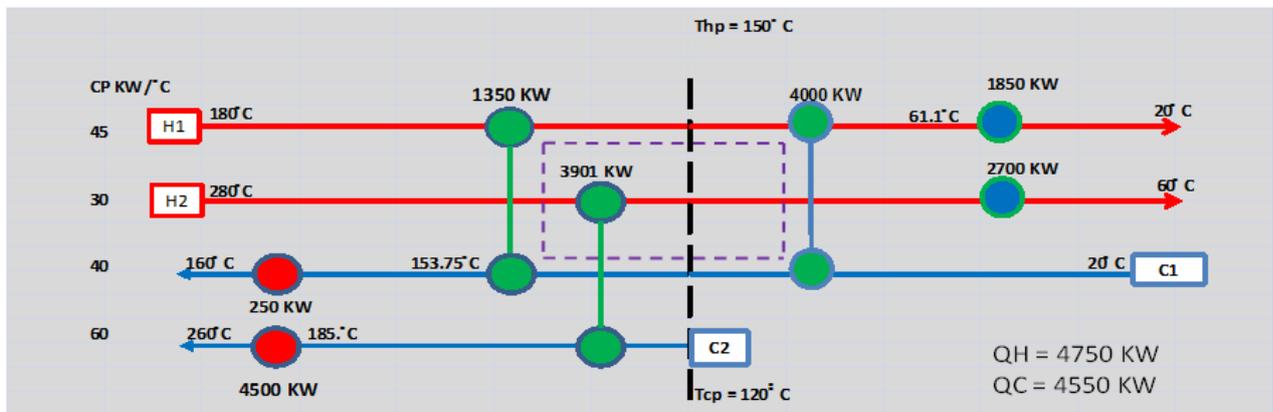


Figure-6.A. HEN of the case study before breaking loop.

Source: Gabr [1].

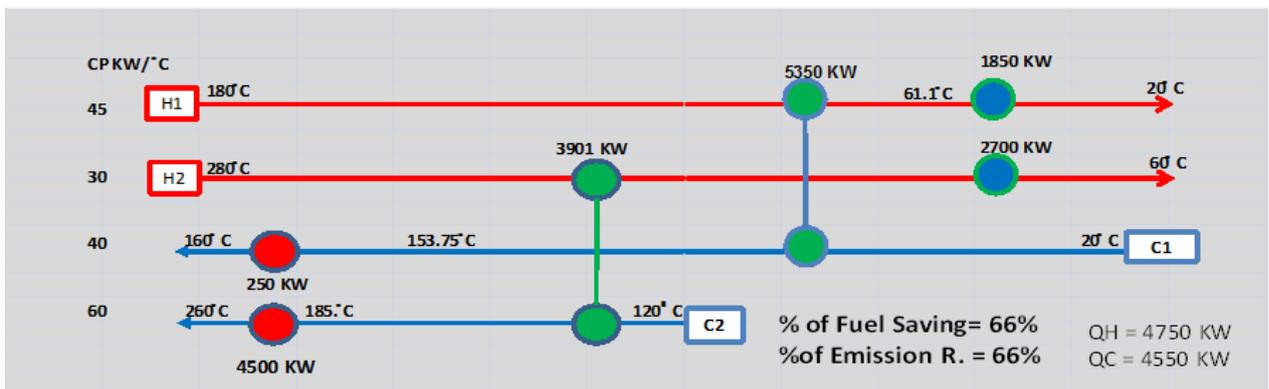


Figure-6. B. HEN of the case study after breaking loop, minimum № of Units.

Source: Gabr [1].

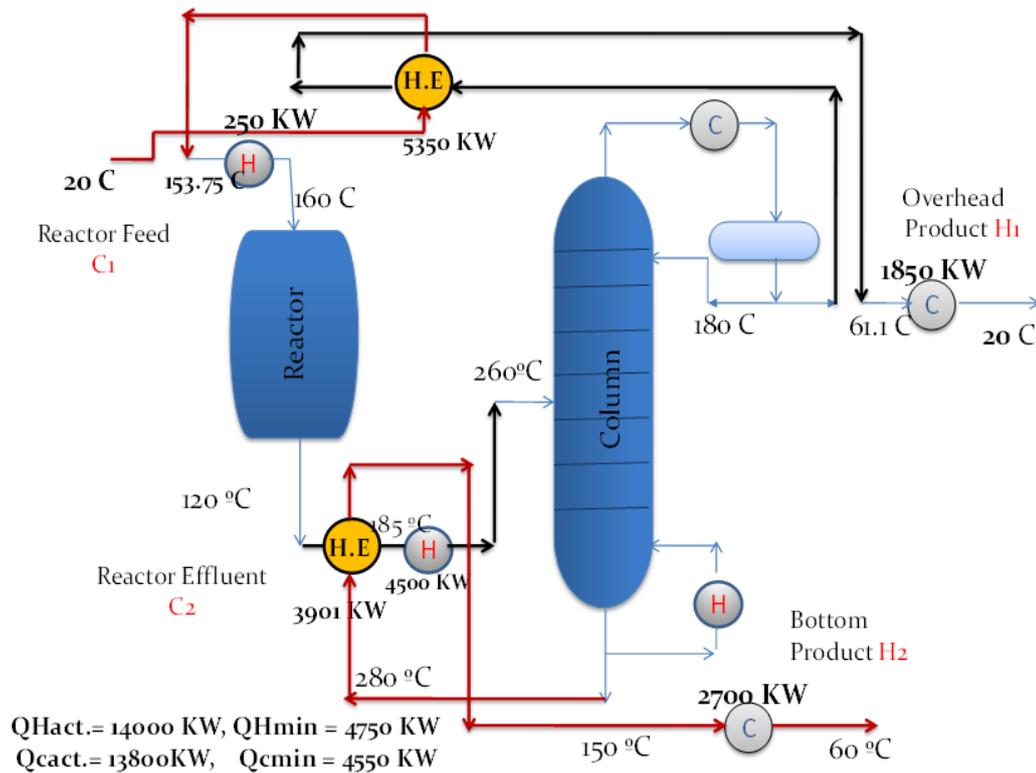


Figure-7. Flowsheet of the Case Study after Revamping.

Source: Gabr [1].

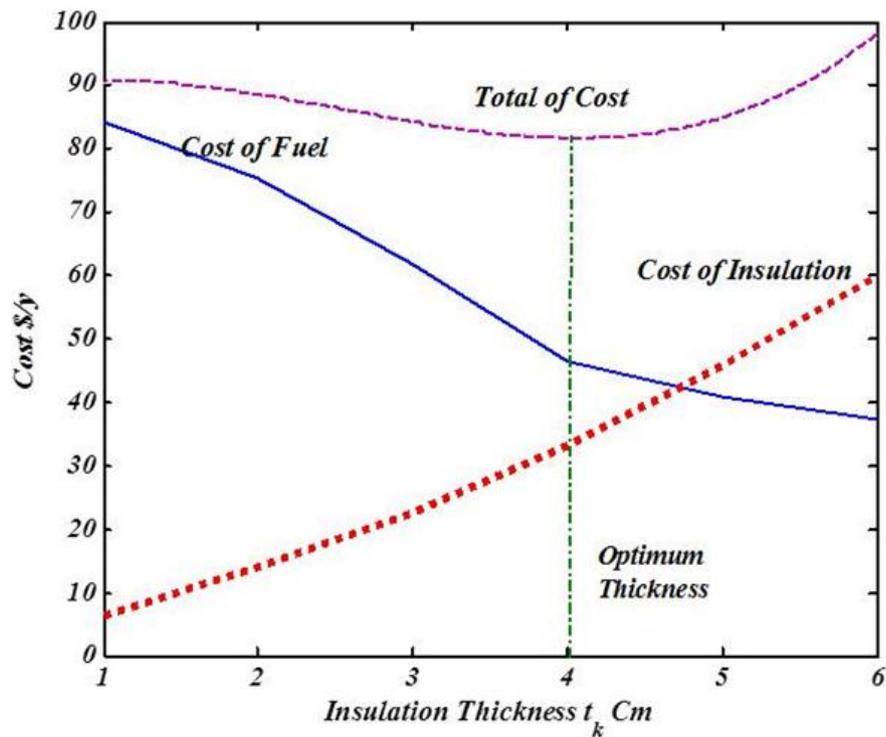
4.2. Second Technique; Reducing of Energy Losses and Emissions of the Case Study by Using Insulation

- The Candidate type of insulation for the case study is Mineral Wool because it has many forms, easy and flexible in processes application and suitable for a wide temperature range with thermal conductivity of 0.044 W/m<sup>2</sup> °C.
- Study the effect of insulation thickness took place, whereas thickness increases surface temperature decreases and energy losses decreases. But at the same time increasing insulation thickness means added cost. Details and results of the application of Equations 11-17 on the case study are listed in Table 3.
- Definition of optimum insulation thickness is shown in Figure 8. Insulation thickness of 4 Cm realized minimum total cost and so on it is the optimum thickness which applied for the case study, where heat loss reduced from 973.51 MJ/h before insulation to be 73.2 MJ/h after Insulation.
- Control of heat loss through optimum insulation application technique achieved % fuel saving of 15 % and subsequently % CO<sub>2</sub> emission reduction of 15 %. That has economically benefits and good environmental impact.

Table-3. Effect of Insulation thickness (tk) on cost of both Fuel and Insulation.

Condi- tions t <sub>ki</sub> Cm	r1 Cm	r2 Cm	T <sub>a</sub> °C	T <sub>s</sub> °C	L m	V m <sup>3</sup>	A m <sup>2</sup>	Cost of Fuel \$/y*10 <sup>-2</sup>	Cost of Insulation \$/y
1	10	11	30	75	100	0.7	69.0	84.1	6.3
2	10	12	30	62	100	1.4	75.4	75.3	14.1
3	10	13	30	55	100	2.2	81.6	61.8	22.7
4	10	14	30	48	100	3.0	88.0	46.4	33.3
5	10	15	30	45	100	3.9	94.2	40.9	45.9
6	10	16	30	43	100	4.9	100.5	37.4	60.1

Source: Results of application the Equations 11-17 on the case study.



**Figure-8.** Effect of insulation thickness on fuel, insulation and total cost Optimum insulation thickness realized minimum total cost.  
 Source: Bureau of Energy Efficiency ([www.pera.org](http://www.pera.org)) results of application of Equations 11-17 on the case study

**4.3. Third Technique; Reducing Emissions of the Case Study through Fuel Switching Technique**

Studying replacement fuel oil with natural gas for the case study realized great results. By application of Equations 1-3 with specifications of both fuels from Table 1; improvement of cost saving and emissions reduction are realized. The results listed in Table 4, where cost-saving reached 58% and emission reduction reached 44%, taking into consideration the cost of the burner and nozzle modification due to switching.

**Table-4.** Summary of results due to fuel switching from Fuel oil to Natural Gas.

	Natural Gas	Fuel Oil
NHV MJ/kg	51.2	40
$\beta$	0.76	0.85
$\phi$	3.5	3.7
CER	0.052	0.079
Cost \$/kg	0.34	0.28
$Q_{fuel}$	54584	64217
Operating Cost \$/y	2206197	5305117
Rate of Emissions ton/y	22542	40000

Source: results of application the Equations 1-3 on the case study.

**4.4. Fourth Technique; Integration between the Three Techniques on the Case Study**

While application the last three techniques separately on the case study achieved good results in control and reduction of CO2 emission, integration between them modified the case study to optimum conditions. The revamped design of the case study by adding two heat exchangers, using the optimum thickness of insulation and replacement of fuel oil with natural gas achieved great results. Comparison between the existing case study and the four techniques results are shown in Figures 8, 9, 10 and 11. The three separate techniques achieved remarkable improvement in both emission reduction and cost saving compared to the existing case. The highest percentage of emission reduction and cost-saving around 80% and 85% respectively can be realized by the integration technique.

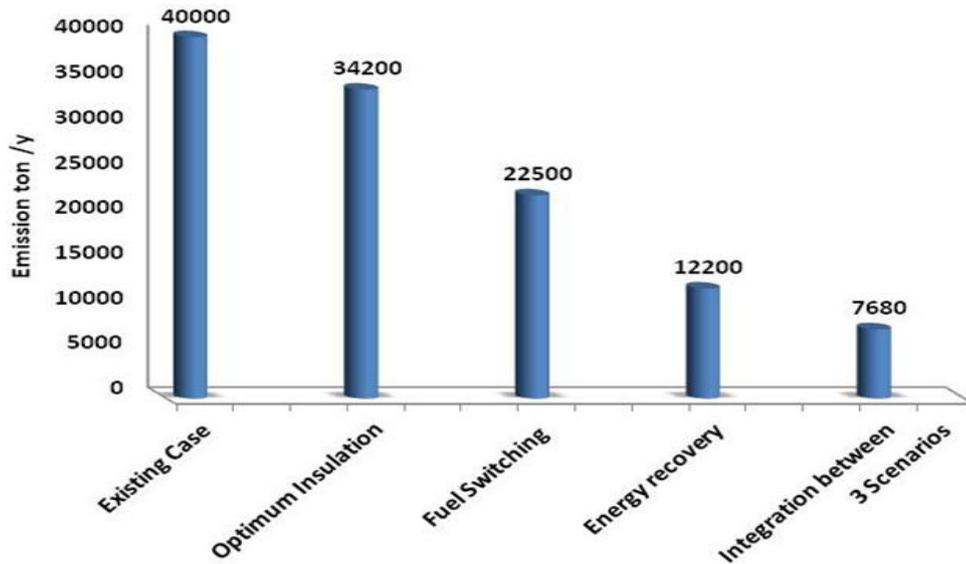


Figure-8. Annual Emission of the existing case compared with application of the three techniques emissions. Source: Bahadori [21].

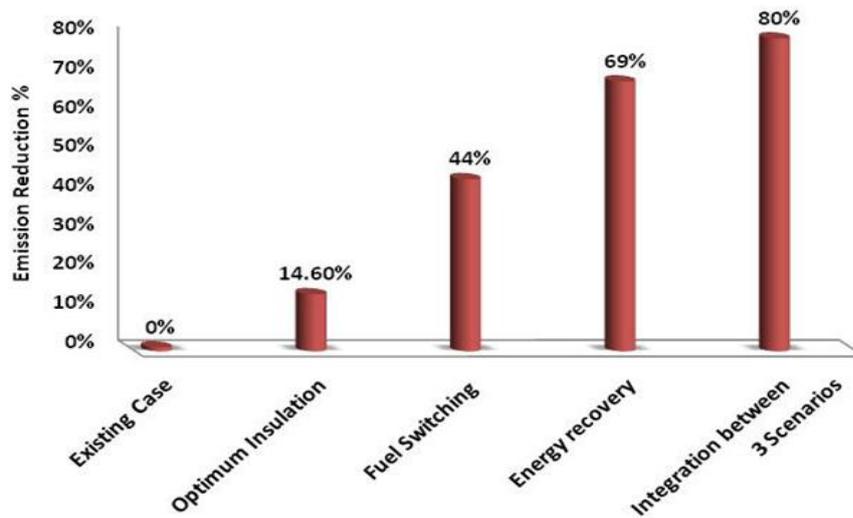


Figure-9. Comparison of Emission Reduction% between existing case and the four techniques. Source: Bahadori [21].

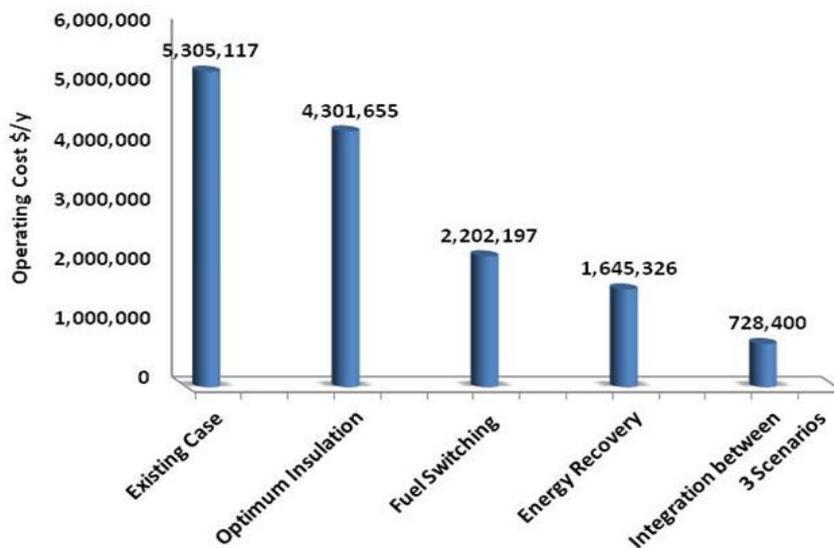


Figure-10. Annual cost of the existing case compared with application of the four techniques. Source: Bahadori [21].

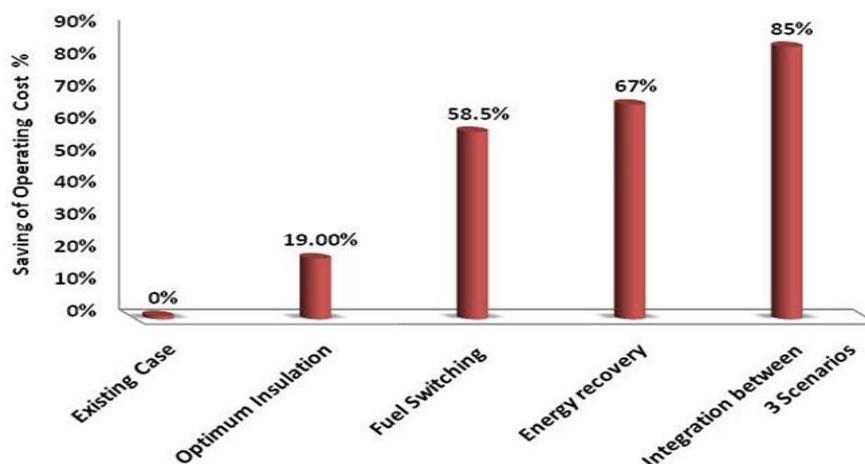


Figure-11. Comparison of Cost saving % between existing case and the four techniques.  
Source: Bahadori [21].

## 5. CONCLUSION

Protection of the environment is a Nobel goal, all institutions, sectors and researchers must do their best in this field. Reducing the harmful emissions of fuel combustion has an effective impact on the environment.

In this work, we succeed in formulating an energy management methodology to conserve energy consumption, reduce energy losses and minimize CO<sub>2</sub> emissions. This methodology is consisting of four techniques; the first one depends on maximizing energy recovery through HEN design to reduce the fuel needed. The second technique depends on minimizing heat losses by application of suitable insulation. Third one guarantees fewer emissions through fuel switching. The fourth technique is the integration of the last three techniques. These several available techniques help the operating engineers to choose and apply the suitable one for his unit.

We applied this methodology with the four techniques in a case study. Firstly, is energy recovery by designing of Heat Exchanger Network (HEN) where 66% reduction of both energy used and combustion' emission achieved.

**Secondly**, is minimizing heat losses by application of optimum insulation thickness where fuel consumption and emission reduced by 15%.

**Thirdly**, Fuel switching by replacement fuel oil with natural gas to reduce emissions by 44% compared to the existing case.

**The fourth one** is the integration between the 3 techniques; where maximum energy recovery achieved through the revamped unite, using optimum thickness insulation and using natural gas as instead fuel. This integration achieved the highest percentage of emission reduction reach to 80%.

## 6. RECOMMENDATION

We recommend applying this methodology on any chemical unit to minimize energy consumption and so on minimize fuel combustion. As fuel combustion decreases, harmful emission decreases which have a good effective impact on the environment. Replacement the used fuel with natural gas is another recommendation to reduce emissions and protect the environment.

### Nomenclature

$\eta_{\text{furnace}}$ : Furnace efficiency (dimensionless)

$T_{\text{TFT}}$ : Theoretical flame temperature (around 1800 °C)

$T_{\text{STACK}}$ : Stack temperature (around 160 °C)

$T_o$ : Ambient temperature C

$Q_{\text{fuel}}$ : Heat duty from fuel

$Q_{\text{proc.}}$ : The process heat duty

$M_{pol}$ : Mass flow rate of pollutant

NHV: the fuel net heating value

$\beta$ : The mass percentage of the pollutant in non-oxide form

$\Phi$ : The ratio of the molar mass of the oxidized form to the non-oxidized form of the pollutant

Q: Heat load of the unit

Area: Heat transfer area of the unit in  $m^2$

$\Delta T_{lm}$ : Log mean temperature difference

$h_i$ : heat transfer coefficient of hot stream

$h_j$ : heat transfer coefficient of cold stream

S : Surface heat loss in kCal/hr  $m^2$

$T_s$  : Hot surface temperature in  $^{\circ}C$

$T_a$ : Ambient temperature in  $^{\circ}C$

$T_{in}$ : Inlet temperature of streams in  $^{\circ}C$

$T_{out}$ : outlet temperature of streams in  $^{\circ}C$

$C_p$ : Heat capacity flow rate in kW/  $^{\circ}C$

Hs: Total heat loss in kCal/hr

$H_f$ : Equivalent fuel loss in kg/Yr

A: Surface area in  $m^2$

NHV: Fuel Net heating value in kCal/kg

$\eta_b$  : Efficiency of boiler in %

$C_f$ : Cost of fuel in \$/Kg

$C_{ins}$ : Cost of insulation in \$/Kg

V: Volume of insulation in  $m^3$

$\rho$ : Density of insulation material in Kg/ $m^3$

r1: Radius of pipe before insulation in m

r2: Radius of pipe after insulation in m

L: Length of pipes in m

$t_i$ : Insulation thickness

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