A THERMAL DESIGN AND ENERGY ECONOMIC ANALYSIS TO PERFORM NEW ENERGY SCHEME FOR AN EXISTING COMBINED HEAT AND POWER (CHP) SYSTEM

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ABSTRACT

World fossil fuel reserves has been decrease for some decades , while world energy consumption has been increased gradually . This energy crisis would encourage all government around the world to improve efficiency used of fossil fuel. The CHP/Cogeneration power plant can be used to minimized the uses of fossil fuel. Considering that situation, it would be study, to improve efficiency of CHP system thermally and economically by performing a new energy scheme for an existing CHP plant. In this study, the existing CHP plant is Diesel Engine JMS 612 V-Cylinder with electric and heat output respectively 2544 kW and 2589 kW, in which there is 1796 kW unutilized heat rejection. On the other hand, there is a presence of a new cooling demand of 800 kW for the site. This new cooling demand would be thermally and economically satisfied by using the unutilized heat rejection to driven a single-effect Lithium Bromide-Aqua absorption chiller. It is found that the integration of a single-effect absorption chiller has gave a new energy scheme for the CHP plant to be a Combined Cooling, Heat and Power (CCHP)/Trigeneration system, in which it produce 2544 kW electric energy, 793 kW heating energy for water and space heating and 800 kW additional cooling energy. In the presence of 800 kW new cooling demand and new energy scheme CCHP system, the system efficiency increases from 48% to 67% and for 8500 hours/year operation, the fuel cost decrease of about 28%. It can be concluded that utilizing CHP heat rejection by integrating single effect absorption chiller into CHP plant ,could produce an additional cooling energy, increase system efficiency and reduce fuel cost.

Keywords : New energy scheme, CHP and CCHP system, power and fuel cost,single effect LiBr/H2O absorption chiller , R-site ratio

1. Introduction

The continuously growing scarcity of primary energy and environmental impact has been encourage to look for any alternatives to traditional energy sources [1]. It has been promoted and supported by many government around the world for the use of renewable energy sources for energy security and environment conservation purposes, such as wind energy, solar energy, ocean thermal energy, etc. In the use of those renewable energy sources, however there are still some technical problem impede any further promoting and commercialization of the new renewable energy sources [2-4]. There should be a better energy sources that can improve energy conservation efficiency [5]. Combined heat and power (CHP) generation or well-known as Cogeneration system, has a high efficiency as it produces both electricity and heat from a single fuel input, in which the unutilized heat has been convert into useful heat [6-8]. It is proven that the use of CHP system could reduce energy consumption for primary energy sources, as well as could reduce pollutant emission to the atmosphere [9]. The CHP system use a single power generation unit as a main source, it could be a micro gas turbine (MGT), fuel cell or an internal combustion engine, in which some or all of by-product would be utilized for heating and cooling or as hot water with temperature range from 80^0C to 130^0C , as a result, the CHP efficiency would increase extremely, environment friendly and cost effective way of supplying electricity, heating and cooling [10-11]. This power generation system with three useful energy produced from a single fuel energy sources is called as Combined cooling, heat and power (CCHP) or Trigeneration system. In the CCHP system, waste heat from primary power generation unit is deriving to the heat recovery section to produce heat or high temperature steam and some part of this waste heat would be derived to an absorption chiller to produce cooling energy. Heating and cooling energy is probably produced simultaneously or intermittently depending on need or system construction.[12-15]

Building would release about 30-35% energy related CO2 emission, as it consumed approximately 30% of total energy world wide. It is necessary to consider the use of different new and promising technologies to reduce energy consumption in building in cost-effective manner [15, 16-18]. CCHP has been widely use for the building, as it can produce three different useful energy simultaneously to meet energy required for the building in environmentally friendly ways. CCHP systems have been consider to be applied to increase system efficiency and alleviate the global warming impact and offer a cost effective system, compare to the use of single primary power generation system. CCHP systems, as well as, has been broadly employed for some building types ranging from multi-family to commercial and office building, even for community.[19-21]. In this study, it would focus on the performing of a new energy scheme for an existing CHP plant thermally and economically. The existing CHP plant is an internal combustion engine based, located in a hospital in Newcastle, UK. It produced 2544 kW electric energy and 2589 kW heat energy which is already used for space and water heating about 793 kW, so that there would be about 1796 kW unutilized heat. Furthermore, the problem emerged as there is a presence of a 800 kW new cooling demand for hospital site. This problem has been encourage to consider either install a new cooling system or utilize waste heat from CHP plant, these two schemes has different thermal and economical design consideration, so that it is motivated within this study it would be performed thermally and economically a new energy scheme to utilize the 1796 kW remaining waste heat from the existing CHP plant respect to the new installing of 800 kW cooling system In order to satisfy this new cooling demand, the remaining waste heat from the existing CHP plant would be derived into a single effect lithium-bromide/water absorption chiller (AC) and thermally design to perform a CCHP system. Broadly study has been conducted to investigate the employed of several cooling technologies for CCHP system. Some cooling technologies including LiBr/Water AC, Ammonia/Water AC, adsorption chiller, desiccant cooling device has been thermally reviewed. The most widely used types of LiBr-H_2O ACs are single effect and double effect. Single effect ACs has only one desorption process, it can recover waste heat with temperature lower than 120^0C , within a COP of about 0.7 . While Double effect ACs has two desorption processes, high pressure desorption process is driven by heating sources with temperature over 120^0C and low pressure desorption process is powered by the refrigerant vapor generated by high pressure desorption process, with COP of about 1.2 or higher [22]. In comparison, ammonia/water ACs can reached evaporating temperature below 0^0C, but its COP is lower than LiBr/Water ACs for the same operating conditions and ammonia is toxic.[23]. On the other hand, Internal Combustion Engine (ICE) is a widely used prime mover for small and medium scale of CCHP system [24]. The temperature of ICE exhaust gas is fluctuated between 40^{00}C and 60^{00}C and the jacket water temperature of ICE would reach 90^0C or higher.[25]. Site survey on the existing ICE based- CHP system results on some technical data in which the exhaust gas temperature leave the engine at 452^0C and drop to 180^0C after passing through a Heat Recovery Steam Generator (HRSG) and Economizer to produce heating sources for space and water heating and then dispersed it through the stack. Considering site survey data above, it would be thermally design the integrating of a single effect LiBr/Water ACs system into the existing ICE based-CHP system to perform a CCHP new energy scheme to satisfy the 800 kW new cooling demand and then compare it economically respect to the produce another 800 kW electric energy for the new cooling demand.

2. System Description

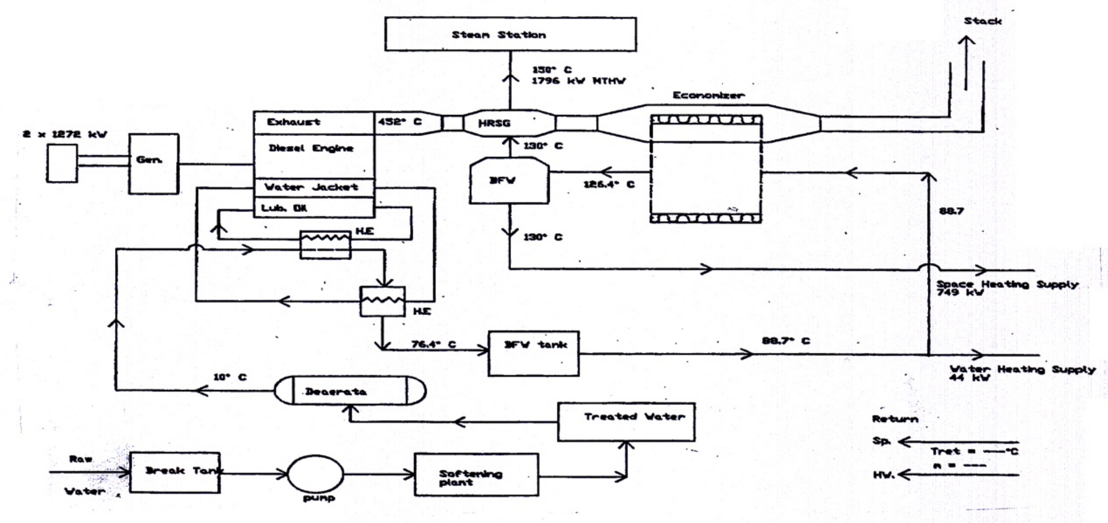
2.1. The existing ICE based-CHP plant description

As it shown in Fig.1, The existing ICE based-CHP plant are two diesel engine type JMS 612 V-cylinder supplying about 2 x 1272 kW electrical energy to satisfy an existing base electric load of about 2532 kW for hospital and staff residence. The cogeneration system mainly provides process steam for space heating and water heating, in which for space heating is used 749 kW medium temperature hot water (MTHW) from boiler feed water after being heated in economizer and water jacket heat exchanger at 130^0C, while for water heating is used 44 kW low temperature hot water (LTHW) from water jacket and lubricating oil at 80^0C . So that there is a total of 793 kW useful heating source and the remaining of 1796 kW MTHW is unutilized heating source and this remaining heat is really a massive and promoting heat sources to be used for another energy demand.

2.2. The new cooling demand for the CHP plant

The existing CHP plant has only produced 2544 kW electric power that is already used to satisfy an existing power demand of 2532 kW, it mean that the presence of 800 kW new cooling energy demand would not be satisfied by the existing power production. This new cooling energy demand obviously would have required an additional 800 kW electric power from the existing CHP plant. The alternative to expand power production capacity would required a massive investment, therefore it would be investigated the possibility of using unutilized heat of 1796 kW to satisfy the 800 kW new cooling demand, by deriving the unutilized heat to powering a single effect LiBr/H_2O absorption chiller and produce cooling energy.

Fig.1. The existing ICE based-CHP plant



2.3. Performances of the existing CHP plant with and without new cooling demand

Table 1 and 2, described the initial performance of the existing CHP plant with and without the new cooling demand, from which it would be analyzed the CHP or Cogeneration efficiency, R-Site Ratio, and Energy Economic Cost.

Tabel 1. Cogeneration Without Cooling Demand.

	Generated (kW)	Demand (kW)	Surplus/Deficit (kW)
Power	2544	2532	12 (+)
Heat	1796 (MTHW) 793 (LTHW)	0.00 793	1796 (+) 0.00

Tabel 2. Cogeneration With Cooling Demand

	Generated (kW)	Demand (kW)	Surplus/Deficit (kW)
Power	2544	2532 800	788 (-)
Heat	1796 (MTHW) 793 (LTHW)	0.00 793	1796 (+) 0.00

3. R-Site Ratio Analysis and Sizing Single Effect LiBr/H_2O Absorption Chiller

3.1. R-Site Ratio Analysis

The presence of new cooling demand for the existing Cogeneration plant, it would then necessary to compare R-site ratio and Cogeneration efficiency and Energy economic performance for the Cogeneration without new cooling demand, the Cogeneration with new cooling demand with additional 800 kW electric energy, and the Cogeneration with new cooling demand using unutilized heat to drive a single effect absorption chiller and transform the Cogeneration into the CCHP/Trigeneration system. In order to determine the ratio between power demand and heat demand for those three circumstance, it would be used Equation (1), in which it would be defined power demand of the site to the heat demand in the site. The R-site ratio can be determined using R-Curve methods with a graphical tool namely The Best Achievable Curve that can identify the improvement of the existing energy system without capital investment and as well as can indicate the most economic modification to cope with a significant change in heat and power demand [26]

$$\text{R-Site ratio} = \frac{\text{Power Demand}}{\text{Steam Demand}} \qquad (1)$$

Cogeneration efficiency would be determined by using Equation (2)

$$\text{Cogen. Efficiency} = \frac{W}{Q\ \text{fuel}}\left(1 + 1/R\right) \qquad (2)$$

For energy economic analysis , it would be determined annually power cost and fuel cost using Equation (3) and Equation (4) with price based on power and fuel price in the site at the time, in which the power price is at 4.920 pence/kWh and fuel price at 0.6 pence/kWh from the data given for fuel price is 20 pence/term which is equal to 0.6 pence/kWh

$$\text{Power Cost} = \text{Power demand (kW)} \times \text{Power price (p/kWh)} \times \text{Operation hours (h/y)} \qquad (3)$$

$$\text{Fuel Cost} = \frac{\text{Fuel Required (kW)} \times \text{Fuel price (p/kWh)} \times \text{Operation hours (h/y)}}{\eta\ \text{cogeneration}} \qquad (4)$$

3.2. Sizing Single Effect LiBr/H2O Absorption Chiller

From Table 1 and Table 2., it can be seen that there is still 1796 kW (MTHW) unutilized, this heat would used to drive the absorption chiller to produce 800 kW new cooling energy demand. In this thermal design process, it would be assumed that the COP absorption chiller is 0.68. Using some Equation below, it would determine heat input required, and mass flow rate of MTHW.

$$\text{Heat input required} = \frac{\text{Cooling Demand}}{\text{C O P}} \qquad (5)$$

The steam/hot water flowrate required to deliver heat input

$$\text{Steam flowrate} = \frac{\text{Heat Input , kW}}{\text{Heat Input Enthalpy, kJ/kg}} \qquad (6)$$

Interpolation on Steam Table , results in the enthalpy of heat input at 150^0C from boiler is given as below,

$$h_{fg}\,(150^0\text{C}) = h_g\,(150^0\text{C}) - h_f\,(150^0\text{C}) \qquad (7)$$

After interpolation on the value of saturated water enthalpy, hf and saturated steam enthalpy, h hg,it is determined the heat input enthalpy, h_{fg} then the heat flowrate can be determined.

3.3. The properties of the absorption chiller components

From schematic diagram of absorption chiller as it can be seen in Fig.2 below, it would be determined the mass flowrate, temperature , enthalpy, and capacity of the absorption chiller (AC) component.

3.3.1. Mass flowrate of ACs components

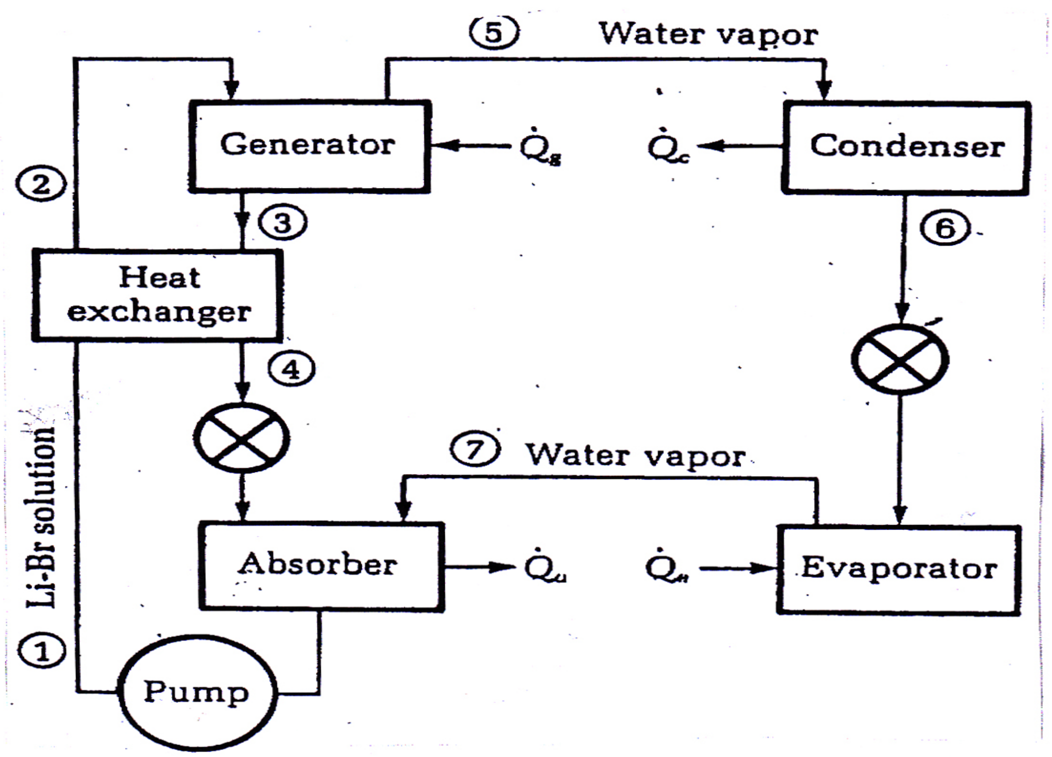
$$\text{Mass flowrate in the solution pump, } W_1 = \frac{\text{Refrigeration capacity,kW}}{\text{Refrigeration effect, kJ/kg}} \qquad (8)$$

$$\text{Refrigerant effect} = Tg_1\,(S_2 - S_3) \qquad (9)$$

Total mass flow balance in generator, $w_3 + w_5 = w_1 = w_2$, this would give total mass flow rate LiBr and H_2O in Generator, w_3 and w_5

(10)

Fig.2. Schematic diagram of Designed Absorption Chiller



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$$\text{COP abs} = \frac{Qe}{Qg} \quad \frac{Te\,(\,Tg - Tamb)}{Tg\,(\,Tamb - Te\,)} \qquad (11)$$

Where : Te = Evaporator temperature, ^{0}C
Tg = Generator temperature, ^{0}C
Tamb = Ambient temperature, ^{0}C (assumed : 20^{0}C)

Absorber and condenser temperature can be determine by applying Ideal COP and given temperature in the generator 120^{0}C as follows :

$$\text{Ideal COP} = -\frac{Te}{Ta} \quad \frac{Tc}{Tg} \qquad (12)$$

In which : Te = evaporator temperature
Tc = condenser temperature
Ta = absorber temperature
Tg = generator temperature

3.3.3. Enthalpies of ACs components

It would be estimated the enthalpies occurred at every single component of ACs system using resulted temperature of ACs component and assumed heat exchanger effectiveness, E = 50%,

As can be seen in Fig. 2 , temperature enter and leaving heat exchanger can be estimated as follows :

$$E = \frac{T_2 - T_1}{T_3 - T_4} \qquad (13)$$

Therefore it can be estimated the solution temperature enter and leaving heat exchanger as :

T_1 = temperature leaving absorber to heat exchanger (HE)
T_2 = temperature leaving HE to generator
T_3 = temperature leaving generator to HE
T_4 = temperature leaving HE to absorber

By re-arrange temperature data, it can be identified the water vapor temperature of ACs component as follows :

$Tg = T_5$ = temperature leaving generator
$Tc = T_6$ = temperature leaving condenser
$Te = T_7$ = temperature leaving evaporator

Having all temperature properties and by using The Enthalpy of LiBr/H2O Solution Diagram, it could be estimated the enthalpies of ACs components as follow

h_1 = solution enthalpy leaving absorber to HE
h_2 = solution enthalpy leaving HE to generator
h_3 = solution enthalpy leaving generator to HE

The solution enthalpy leaving HE to absorber, h_4, can be determined by applying the heat rate absorbed by the solution leaving absorber to generator which is the same heat rate for the solution leaving generator to absorber.

$$Qhe = w_1 (h_2 - h_1) = w_3 (h_3 - h_4) \qquad (14)$$

As all the solution enthalpy have been determined, the remaining enthalpies are the enthalpy of water liquid and water vapor that can be estimated using Steam Table

h_5 = the water vapor enthalpy leaving generator
h_6 = the water liquid enthalpy leaving condenser
h_7 = the water vapor enthalpy leaving evaporator

3.3.4. Capacity of ACs components

Having all those properties of ACs components including temperature, mass flowrate, and enthalpies, it then can be determined the capacity of ACs components

Generator capacity, Qg = heat absorbed in generator = $w_5h_5 + w_3h_3 - w_2h_2$ (15)
Absorber capacity, Qa = heat rejected by absorber = $w_7h_7 + w_4h_4 - w_1h_2$ (16)
Heat exchanger capacity, Qhe = heat transferred in HE = $w_1 (h_2 - h_1)$ (17)
Condenser capacity, Qc = heat rejected by condenser = $w_5h_5 - w_6h_6$ (18)
Evaporator capacity, Qe = heat absorbed in evaporator = $w_7 (h_7 - h_6)$ (19)

4. Results and Discussions

4.1. Thermal Design

Thermodynamic analysis and design of the absorption chiller system indicated that an absorption chiller system can be integrated into an existing CHP system by utilizing waste heat from the existing CHP which is supplied to the generator of ACs system and produce cooling energy. It can be seen from Table 3. that the exhaust heat rejected from the existing CHP plant can be thermally design and performed into a CCHP system within their capacity as following :

The generator of designed ACs require 1295 kW waste heat from the existing CHP plant to be deliver, while the absorber would reject 1207 kW to the surrounding and from the condenser 1115 kW heat would be rejected , and at the same time , the evaporator would absorb about 1027 kW cooling load. This designed ACs system is thermally utmost feasible to be developed, as a massive waste heat of 1295 kW , it is about nearly three quarter of total waste heat available (1796 kW) from the existing CHP system that can be utilized into an useful cooling energy and would possible to satisfy the new cooling energy demand of the site. As a single effect ACs system, it only has one desorption process that can recover waste heat with temperature lower than 120^0C, so that it would reject a massive heat to the surrounding, and its COP usually about 0.7 [22]. In this design, there is still about 2322 kW waste heat should be reject to the surrounding and this would require another cooling energy demand either using electrically –driven water/air system or applying double effect ACs system that can recover a higher waste heat grade over 120^0C,[22] as it has two stage desorption process, higher and lower desorption process which would require much more heat than single effect ACs.

Table 3. Thermodynamic properties of absorption chiller component.

Point	Temperature T (^{0}C)	Flowrate w (kg/s)	Concentration X (%)	Enthalpy, h (kJ/kg)	Capacity, Q (kW)
1	15	1.02	30	-160	-
2	66	1.02	-	-20	-
3	120	0.55	56	5	-
4	15	0.55	-	-225	-
5	120	0.47	-	2706	-
6	82	0.47	-	335	-
7	10	0.47	-	2520	-
Generator					1295
Absorber					1207
H.E					143
Condenser					1115
Evaporator					1027

As can be seen in Table 3, it can be discussed that the generator would receive 1295 kW heat from recovery CHP plant waste heat, and then heating the incoming solution from HE at 15^0C to be a strong water vapor at 82^0C which then pass through to the condenser and the weak water vapor would pass through to the absorber ,after being cooled by transferring heat to the solution from the absorber which increase solution temperature into 66^0C. There is heat transfer process in the HE, in which the solution from the absorber to generator with enthalpy h_1 = -160 kJ/kg (deficit heat) receive heat from the weak water vapor from generator to absorber with enthalpy h_3 = 5 kJ/kg ,therefore the deficit heat of the solution from absorber to generator become decrease to h_2 = - 20 kJ/kg. On the other hand, the weak water vapor from generator to absorber become deficit heat to h_4 = - 255 kJ/kg. As a result, the generator would require less energy for heating the solution LiBr/H_2O and the absorber as well as would require less cooling energy to reject heat to the surrounding.

4.2. Energy Economic.

From the energy economic point of view, the new energy scheme for the existing CHP plant in which it recover unutilized heat to produce cooling energy and transform the CHP plant into the CCHP plant, by thermally integrating of the single effect LiBr/H_2O ACs to the existing CHP plant and satisfy the new cooling energy demand, this integration would improve the efficiency of the CHP plant, as the unutilized heat can be used to produce another useful energy, rather than produce another electric energy to satisfy the new cooling energy demand. As a result, the improve in efficiency of CHP plant would cause the reduction of power and fuel cost.

Table 5. The changes of energy efficiency and energy economic of the existing CHP plant.

Existing CHP Plant Scheme	Power demand (kW)	Heat demand (kW)	Heat surplus (kW)	Cooling Produced (kW)	System Eff. (%)	Power Cost (£/year) 1E3	Fuel Cost (£/year) 1E3	Total Cost (£/year) 1E3
A	2532	793	1796	-	48	1,059	693	1,732
B	3332	793	1796	800	45	1,394	702	2,096
C	2532	1970	620	800	67	1,059	502	1,561

Note : Scheme A – CHP Without cooling demand
Scheme B - CHP With cooling demand by producing another 800 kW electrical energy
Scheme C - CHP With cooling demand by utilizing 1176 kW waste heat plants

It can be seen from Table 5, the efficiency of the existing CHP plant increase and reduce total cost as there is an effective recovery for the unutilized waste heat. Total cost would decrease due to the increasing of heat/steam demand, so that the R-site ratio decrease, the efficiency of CHP plant increase and in turn would reduce fuel cost. Furthermore, it can be indicated that in term of satisfying a new cooling energy demand for an existing CHP plant is proven more effective to use the unutilized waste heat respect to the produce another electric energy to satisfy the new cooling demand. On the other hand, utilizing waste heat from the existing CHP plant could increase efficiency of the system, while the CHP efficiency would decrease when producing another electric energi due to the increasing of power demand would increase the R-site ratio as well as the fuel cost would increase. The utilizing of the CHP waste heat to produce cooling energi has caused the increasing of the CHP plant efficiency from 48% to 67%, while the annual fuel cost would reduce from £ 693,000 to £ 502,000 or reduce about 28%, it is a significant saving fuel for the site CHP plant. Meanwhile power cost is remain the same as there is no demand to produce another power/electric energy for the new cooling energy demand. In addition, after utilizing waste heat for the 800 kW new cooling demand, there is still unutilized heat of about 620 kW, that in the future it can be used for producing heating energy and or cooling energy.

5. Conclusions

In term of energy and energy economic efficiency, the decision to utilize waste heat rather than produce another power energy to satisfy the new cooling energy demand for the existing CHP plant should be became a better and effective decision. When more unutilized heat from the CHP plant can be recover to produce another useful energy, would give the increasing of CHP efficiency, reduce at least the fuel cost. The chose of the single effect LiBr/H_2O ACs to be integrated into the existing CHP plant and performed CCHP system is taken based on the heating sources available has temperature lower than 120^0C, this meet temperature required for single effect ACs, as it only has single desorption process that can only recover heat from waste heat with temperature lower than 120^0C. However, the integration the single effect ACs system has given some beneficial thermally and economically. In this study, the designed single effect LiBr/H_2O ACs has met the heating sources available, met the new cooling energy demand, improve CHP plant efficiency , reduce fuel cost and give benign environment impact as the heat should be rejected to the surrounding has reduce significantly, in this case is about 34%. As well as , it should be considered the limitation of this research, in which this research results could only give a specific suggestion for solving energy demand problem when there is an unexpected new energy demand to the existing site plan especially a CHP plan with a massive unutilized heat. On the other hand, for the policy maker, it would be learned that a more effective energy policy could be established to the public and or private energy company by maximized the use of the CHP unutilized heat instead produce another electrical energy. This scheme could keep a lower energy price and carbon emission which gives a benign environment impact. The government could encourage the developing of CHP system by adopting a policy of incentives [27]

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