A Review of Combined Heat and Power Systems for Hospitals Applications

Daramola Oyewole Olufemi

Abstract - This study aims at investigating the applicability of combined heat and power systems in NHS Trusts hospitals in the United Kingdom. The ever-increasing demands for quality and reliable energy for ventilation, space heating, hot water and sterilization of medical tools are well investigated in this study using data gotten from NHS Trust official site. Reduction of CO_2 emission in the UK hospitals was also investigated. From data gotten from NHS Trusts official website, it was observed that CHP technology is a reliable source of heat and power for hospitals to run their day to day activities.

Index Terms - combined heat, power system, hospital energy, CHP optimization

1 INTRODUCTION

Combined Heat and Power Systems are also called the cogeneration systems. These systems involve the simultaneous usage of heat and power from a single energy or fuel source at the point of use or close to it. An optimal CHP system is designed to meet the heat demand of the energy user- whether at building, city-wide levels or industry- because it doesn't cost much to transport surplus electricity than excess heat from a CHP plant. For this reason, Combined Heat Power can be viewed as a primary source of heat, with electricity as a by-product [1].

Also, CHP can be of many forms and encompass different types of technologies, but will always be required to be an efficient, integrated system that combines electricity generation and a heat recovery system. CHP plants generally convert 75-80% of the fuel source into useful energy through the use of the heat output from the electricity production for heating or industrial applications while most modern plants attain efficiencies of 90% or more [1]. In addition, CHP plants reduce network losses because they are located near the end user (International Energy Agency).

Nowadays, the use of CHP systems in commercial and institutional buildings has increased appreciably. Some of the applications are mentioned in [2]–[6].This is as a result of technical improvements and cost-reductions in smaller scale, often modified, systems that meet the thermal and electrical requirements. Examples of commercial and institutional Combined Heat and Power systems users include offices, hotels and hospitals, which tend to have significant energy costs as a percentage of total operating costs, as well as balanced and constant electric and thermal loads[1].

Hospitals are the best candidates for Combined Heat and Power (CHP) systems. This is largely due to the fact that hospitals are in operations for 365 days a year, 24/7, they demand round-the-clock energy. CHP systems assist hospitals to reduce energy costs, improve environmental performance and augment reliability of energy [7]. This study looks into the critical analysis of CHP usage in hospitals.

2 BASIC ISSUES AND HOSPITAL ENERGY REQUIREMENTS

The consumption of energy in hospitals is growing steadily. Fifty percent of a hospital's energy costs come from electricity and with the increased use of specialist medical equipment that generally relies on electricity, consumption is set to increase [8]. Due to this ever-increasing energy consumption, the need for the use of CHP systems in all NHS Trust hospitals in the UK becomes necessary. This is evident by the statistics generated by NHS Trusts between 1999 and 2005 as shown in the Table 1 below:

Table 1: Energy Statistics for NHS Trusts in England [4]

Year	Total CO_2 emissions (Tonnes)	No. of CHP units	Total Energy Consumption (GJ)
1999/2000	3051258	118	41844492
2000/2001	3177593	104	44134936
2001/2002	3447302	98	46684793
2002/2003	3458351	116	46615416
2003/2004	3470798	112	45951700
2004/2005	3399604	104	44785176

In addition to the ever-increasing energy demand, the UK government Climate Change Act of 2008 which targets an 80% reduction in the Green House Gas emission below 1990 level by 2050 requires the use of CHP systems in the health sector in order to achieve these targets. It can be clearly seen from table 1 above and figure 2 below that the emission of CO_2 in the NHS trust hospitals decreases when large number of CHP systems were employed.

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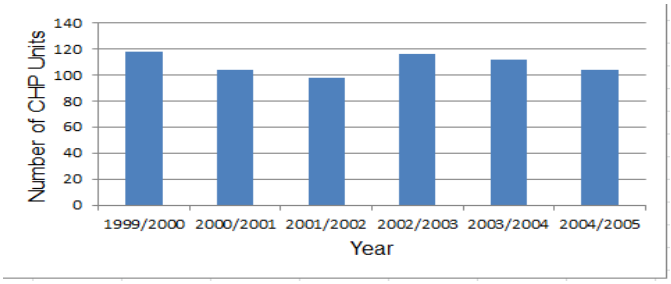


Figure 1: Trend of CHP usage in NHS hospitals between 1999 and 2005

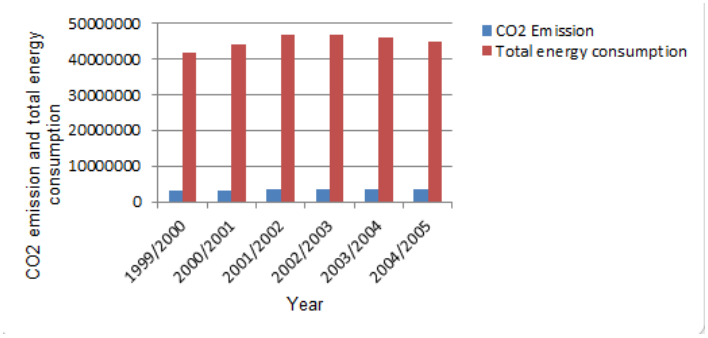


Figure 2: Trend of CO2 emission and total energy consumption between 1999 and 2005

3 THE NEED OF COMBINED HEAT AND POWER SYSTEMS IN THE HOSPITAL

Hospitals are critical infrastructures, thus, if not well incapacitated with the necessary energy facilities, it could have negative effects on public health and safety. Since hospitals operate 24/7, they demand significant electrical power, heating and cooling. Combined Heat and Power systems help to reduce operating costs and higher reliability of continued service[9]. In the UK, the health sector is one of the largest users of energy. The number of NHS hospitals in the UK is approximately 1200 and the potential for CHP has been estimated to be greater than 570We. Therefore, there is significant potential for additional CHP in the NHS [10], [11].

During the occurrence of electrical grid failures due to overloads, storms and security breaches, a reliable energy system is needed for critical safety, lighting, ventilation and heating, medical infrastructure and hot water production in the hospital. Thus, CHP can be used to provide reliable off-grid power during major disruptions and extremely bad weather conditions. Hospitals with CHP do not need to operate stand-alone emergency generators. CHP system is a very good power source in the hospitals since it supports emergency features such as black start capability, seamless change from on-to-off-grid power, ensuring reliable uninterrupted patient care and protecting valuable assets such as diagnostic labs, pharmaceutical supplies and medical research facilities [12].

Contingency plans such as use of CHP, can be made against power outage occurrence to prevent medical facility evacuations to save lives. Since medical care and routines can be disrupted by moving patients from one location to another, causing high risk of hospitalization and even death [12]. For example, a CHP plant has been in operation at Northampton General Hospital since 1989. During a major incident exercise, the hospital recorded large number of casualties when a serious accident was simulated. The hospital thought it vital to simulate a total boiler failure. This catastrophic failure of the boiler house meant that no heat or hot water could be produced. Fortunately, the installed CHP saved the day by supplying the hospital with its needed electricity and heat. Best medical care and attention were given to the patients through the use of CHP as an emergency backup [10].

Finally, the needs to save money and reduce greenhouse gas emission in hospitals call for the use of CHP. CHP systems save money and reduce emission through decrease in energy grid purchases while ensuring better patient outcome [12], [13]. For example, Montagu hospital in the United Kingdom is a one hundred and thirteen bed community and acute services hospital that is saving one hundred thousand pounds each year from CHP. This CHP plant was integrated with energy management system (BEMS) control, heating system and boiler which enabled energy cost savings over and above those expected. These additional funds were included in a small budget to support further energy efficiency schemes. This unit has performed excellently that the NHS Trust is considering a much larger CHP for the Doncaster Royal Infirmary[10].

4 TYPES OF CHP SYSTEMS APPLICABLE FOR HOSPITALS

Combined Heat and Power systems consist of five basic components: a prime mover (drive system or engine), an electric generator, a heat recovery system, a control system and an exhaust system. While the prime mover drives the electric generator, it creates usable heat that can be recovered. CHP units are classified based on the type of application, prime mover and fuel used. The figure below (Fig. 3.0) shows the various components of a CHP power plant:

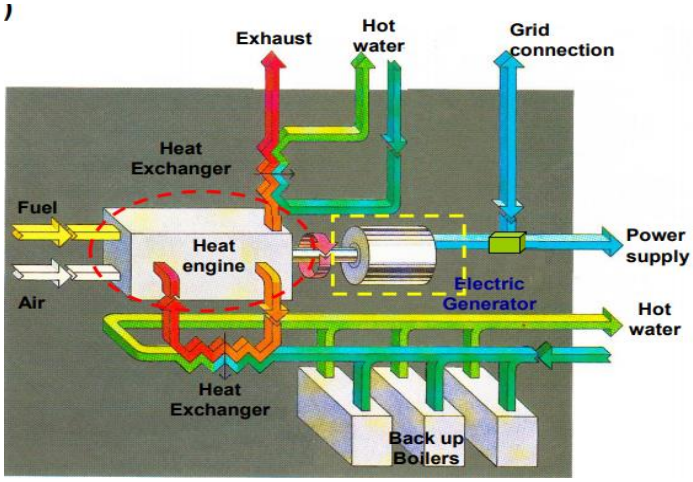


Figure 3: Components of a CHP Plant [8]

The two most common CHP systems used in the hospitals based on 24hours of operation, CHP power output (less than 2MWe) and hot water and steam demand are as follows:

(a) Internal Combustion Engines Cogeneration Systems:

This can be either the spark ignition internal combustion engine CHP system or compression ignition engine CHP system. The spark ignition internal combustion engine CHP system is highly used than compression IC engine CHP system in the hospitals due to its low noise production, as hospital is a place where noise must be reduced to the lowest level. Also, the spark ignition IC engines CHP systems usually consist of diesel engines converted to run on natural gas. The heat recovery is from engine coolant and exhaust and low-grade heat is produced with a temperature greater than 100℃ , which is compatible with LP boiler. The electric power rating of a spark IC engine cogeneration system ranges from 5kW to 2MW, with a heat to power ratio (HPR) of 2 to 1 and heat to power conversion efficiency of 35%[14].

Compression Ignition engine CHP plants produce power output up to 15MW and efficiency of 35-45%. Combustion starts on contact as the fuel is injected into the compressed hot air and air is compressed to a temperature that is above the auto-ignition temperature of the fuel. The temperature of the cooling water is low, typically around 85℃. The compression ignition engine CHP plant operate on high excess combustion air, with a possibility of supplementary firing and a less refined diesel can be used as fuel. Compression Ignition engine CHP plants are not widely used in the hospitals due to their noise-making ability during operation [14], [15].

In conclusion, Internal Combustion Engine Cogeneration Systems (mostly spark ignition IC engine CHP plants) are widely used in the hospitals due to their low capital cost compared to gas and steam turbines. Also, their long-expected service life of 15 to 25years made them a better option for hospitals. Despite the fact that internal combustion engines have low power to weight ratio, which made a strong foundation a requirement for them, they are still widely used in the United Kingdom [14] [16]. This can be seen from the evidence provided in Figures 4.0 and 5.0 below:

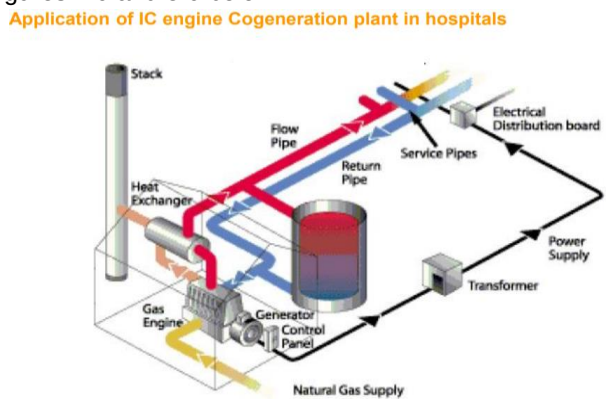


Figure 4: Schematic Diagram of an internal combustion engine cogeneration plant for hospital [8].

NORTHAMPTON GENERAL HOSPITAL

Trust	Northampton General Hospital NHS Trust
Size	740 beds
Type	Acute services
CHP	1 × 85 kWe (region funded) 1 × 220 kWe 1 × 450 kWe
Date	1989, 1995 and 1997
Engine	Spark ignition
Funded	Capital purchase
Saving	£70 000 per year

POOLE HOSPITAL, DORSET

Trust	Poole Hospital NHS Trust
Size	720 beds
Type	Acute services
CHP	1 × 380 kWe
Date	1994
Engine	Spark ignition
Funded	Discount energy purchase
Provider	Nedalo
Saving	£33 000 per year

Figure 5: Examples of UK Hospitals that uses Internal Combustion Engine CHP [6].

(b) Gas Turbine CHP System:

The gas turbine cogeneration system consists mainly of the following components: gas turbine engine, supplementary firing burner, generator, and waste heat recovery boiler. In this CHP system, air is taken in, compressed and burned with a fuel (mostly natural gas), and then released to drive a turbine that generates power. At the same time, heat is produced, and this can be recovered from the exhaust and put to use in the hospital units for cooling, heating and sterilization.

The power rating for a gas turbine cogeneration plant ranges from few kW to 250MW, though a power rating of less than 25MWe is needed for hospital operation. Also, gas turbine CHP systems produce high grade heat to steam generation and they have high exhaust temperatures 400-600℃, these make the steam produced a good means of sterilization in the hospitals[14], [17]–[19]. Figure 6.0 shows a typical gas turbine cogeneration system, while figure 7.0 gives the details of QMC

Nottingham NHS Trust as an example of hospitals that use the gas turbine CHP system:

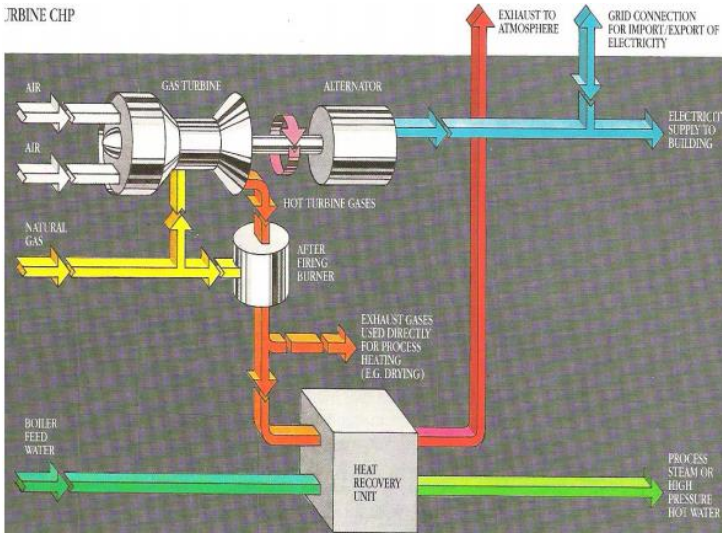
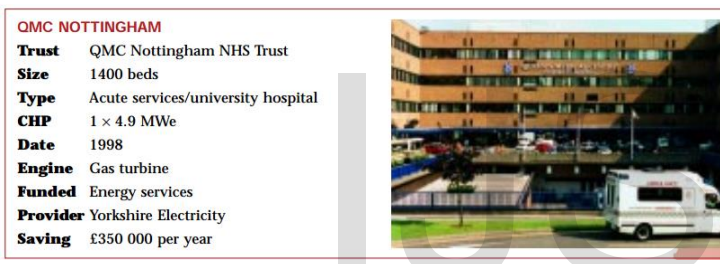


Figure 6: Schematic diagram for gas turbine cogeneration plant for hospitals [8].



QMC NOTTINGHAM	
Trust	QMC Nottingham NHS Trust
Size	1400 beds
Type	Acute services/university hospital
CHP	1 × 4.9 MWe
Date	1998
Engine	Gas turbine
Funded	Energy services
Provider	Yorkshire Electricity
Saving	£350 000 per year

Figure 7: QMC Nottingham hospital which uses gas turbine cogeneration plant [6].

Internal Combustion Engine CHP systems are more applicable in the hospital than the gas turbine CHP system because of the high level of noise produced by the gas turbine engine and the low mechanical efficiency of the gas turbine CHP systems.
Other emerging CHP technologies that can be employed in the hospital include the microturbine CHP systems, Stirling engine CHP systems, fuel cell technology CHP system. All these emerging CHP technologies will be well discussed later in this report under the section titled "future trends of CHP systems in the hospitals".

5 PERFORMANCE ANALYSIS AND OPTIMIZATION OF CHP SYSTEMS IN THE HOSPITALS

Considering figure 8.0 shown below as a typical CHP plant used in the hospital:

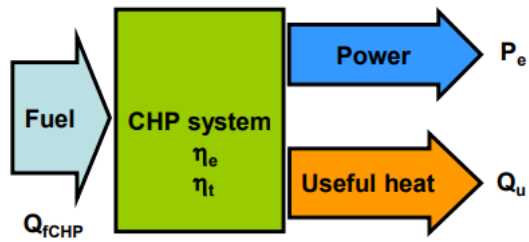


Figure 8: Typical CHP system showing operational parameters.

The performance of a combined heat and power system can be evaluated based on the parameters listed below:

(a) Electrical power conversion efficiency: This is the most important parameter that needs to be maximized as power is high grade form of energy. It is given by the expression:

$$\eta_e = \frac{P_e}{Q_{fchp}}$$

$where\ Q_{fchp} = \dot{m}CV$

(b) Useful heat energy (thermal) generation efficiency: It is the ratio of the useful heat to the heat produced from the burnt fuel.

$$\eta_t = \frac{Q_U}{Q_{fchp}}$$

(c) Overall thermal efficiency: It can be calculated using the formula below:

$$\eta_{CHP} = \frac{P_e + Q_U}{Q_{fchp}}$$

(d) Heat to power (HPR): This is an important parameter when selecting a CHP system to match heat and power demand of a hospital site.

Heat to power ratio, HPR $= \frac{Q_U}{P_e}$

(e) Heat Rate (HR): The ratio of the amount of fuel energy input to power output.

$$\text{Heat Rate HR} = \frac{Q_{fCHP}}{P_e}$$

(f) Fuel Energy Saving Ratio (FESR): This is the ratio of primary fuel energy saving 'ΔG_f' to the total fuel required by power station and boiler 'G_{fG+B}'.

$$\text{Fuel Energy Saving Ratio, FESR} = \frac{\Delta G_f}{Q_{fG+B}}$$

6 OPTIMIZATION MODEL

The optimization of a hospital's cogeneration system can be done using a techno-economic optimization model, which involves the maximization of the annual worth 'AW'[20]. The maximization of the annual worth is defined as a non-linear objective function with nonlinear constraints as shown below:

Objective function:

$$\text{Maximize AW} \rightarrow \text{Max}\ (R_{sell} + C_{avoided} + R_{CO2} + R_{res} - C_{inv} - C_{fuel} - C_{maintenance}).$$

Where $R_{sell} = E_{prod} - P_e$, $C_{avoided} = P_{fuel} \times (\frac{Q_{CHP}}{\eta_b})$, $R_{res} = \psi \times C_{inv}$,

$$R_{CO_2} = P_{CO_2} \times FE_{CO_2} \times t \times E_{prod},\ C_{inv} = \sum_i C_i \times CRF,$$
$$C_{maintenance} = \varphi \times C_{inv},\ C_{fuel} = P_{fuel} \times \dot{m_{fuel}} \times LHV \times t$$

Decision variables: Four parameters are taken as the decision variables, this include: compressor pressure ratio (r_c), air temperature at internal preheater (T_3), combustion gases temperature at turbine inlet (T_4) and the electrical production ($\dot{W}$).

$$3.0 \leq r_c \leq 6.0$$
$$500 \leq T_3 \leq 1000$$
$$1000 \leq T_4 \leq 1400$$
$$90 \leq \dot{W} \leq 120$$

Constraints: The amount of primary energy is taken as the constraint; this is expressed as:

$$\text{Amount of primary energy 'PES'} = \left[1 - \frac{1}{\frac{\eta_{th_{CHP}}}{\eta_{th_{ref}}} + \frac{\eta_{e_{CHP}}}{\eta_{e_{ref}}}}\right]$$

7 ADVANTAGES AND LIMITATIONS OF CHP SYSTEMS IN HOSPITALS

The advantages of using a CHP system in the hospital include:

(a) It reduces energy cost: CHP generates significant annual operational cost savings because there is likelihood of displacing as much as one-third to one-half of the overall energy expenditures at a facility by generating on-site power and thermal energy. This enables CHP systems to pay back the initial capital, and the savings continue beyond the payback period.

(b) CHP systems can offer new sources of income to hospitals if they sell excess electricity to a utility if protocols and agreement can be arranged.

(c) The additional revenue and the savings from energy bills can be reinvested in facilities to support hospital facility expansion and other projects.

(d) CHP systems provide quality backup power whenever there is power outage in the grid.

(e) CHP offers easier hospitals' energy capacity expansion as it can be quickly installed.

(f) CHP systems reduce the emission of greenhouse gases in hospitals. For example, a gas turbine CHP unit with power capacity of 5MW and overall efficiency of 75% reduces annual CO_2 emissions by about 50%[21] .

The limitations of using CHP systems in the hospitals can be classified as shown below:

(a) Economic Limitations: High capital cost, unstable price of natural gas, high operating cost etc.

(b) Customer and Stakeholders limitations: limited on-site space and suitable loads, lack of management support, lack of technical expertise etc.

(c) Limitation from regulations: interconnection of grids, permitting etc.[22]

8 FUTURE TRENDS OF CHP SYSTEMS IN THE HOSPITALS

Between now and 2050, the use of small-sized, efficient, low maintenance and low emission technologies will be used in the hospitals for generating both heat and electrical power. These future and emerging CHP technologies to be used for CHP systems in the hospitals include:

(a) Microturbine: These are small gas turbines that use modified structures and processes to produce heat and power. They consist of a compressor, a combustion chamber, a turbine and a recuperator that transfers heat from the exhaust gas to the intake air. This preheating of the intake air reduces the amount of fuel needed for ignition in the combustion chamber, thus increasing energy efficiency.

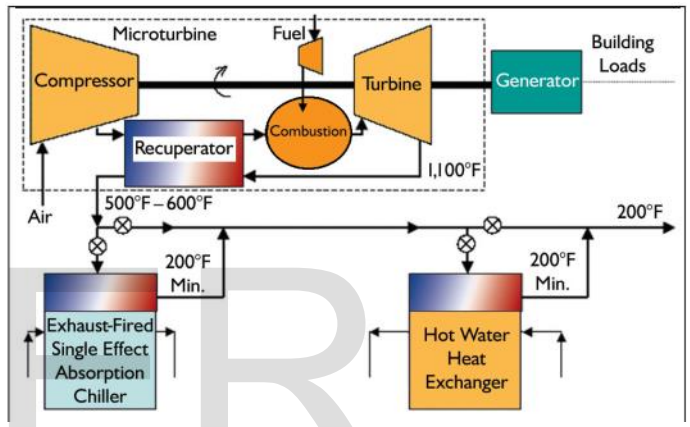


Figure 9: A micro-turbine based CHP system [12].

(b) Fuel cell: Fuel cells are electrochemical devices that convert hydrogen fuel
directly to electricity and heat without combustion. It has high efficiency about 70% and its suitability to wide range of heat and power loads makes them applicable to hospitals. Fuel cells have no moving parts, as a result of this, there is no need for lubricants. Hence, more running cost is saved. Figure 8 below shows the schematic diagram of a fuel cell.

(c) Stirling engine: An assembly of Stirling engines will emerge as a source of power and heat in the hospitals in future. The future applicability of Stirling engine in the hospitals is due to the following: low noise, low vibration, overall efficiency of 90% and an electrical efficiency of about 12%.

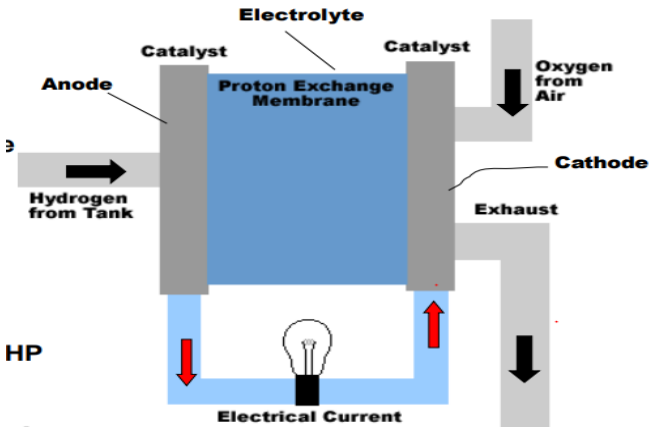


Figure 10: Fuel cell diagram [14].

Other future CHP technologies that will be used in hospitals include steam turbines, organic rankine cycle engines and small reciprocating engines.

9 CONCLUSION AND REFLECTION

From this study, it is seen that the increase in the demand of energy in the health sector has increased tremendously. This demand of energy is needed for some operations and processes such as ventilation, space heating, hot water demands, medical tools sterilization among others. Thus, the need for quality and more reliable power and energy source arise. Consequently, CHP systems are seen to be more effective and reliable source of power and heat in the health sector of the United Kingdom.

Also, certain factors need to be considered in the installation of CHP systems in hospitals, these include: organizational financial targets, anticipated operations and maintenance costs, compliance with air quality requirements, compliance with local ordinances among others [7], [23]. Internal Combustion engine CHP systems are seen to be widely used in most UK hospitals, with technologies like microturbines, Stirling engines, fuel cells etc. having a positive prospect of being used in the hospitals in the nearest future [24], [25].

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