COMBINED COOLING HEAT & POWER (CCHP) IN SUPERMARKETS

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ABSTRACT

With recent initiatives from the UK government on reduced energy use, energy efficient systems such as CHP have been considered for new applications, including supermarkets. In these commercial buildings, the seasonal demand for heat results in underutilisation of the CHP equipment, limiting the primary energy savings that may be achieved. To increase the utilisation time, it has been proposed that heat generated by the CHP unit could be used to power an absorption refrigeration system providing cooling for the refrigerated cabinets. The application of an integrated CHP /absorption scheme or Combined Cooling Heat and Power (CCHP) in the supermarket is the subject of this paper.

The paper initially describes the cooling / heating / power requirements of a typical supermarket and then reviews a number of CCHP options involving the use of different cooling and engine technologies. The investigation calculates and compares the energy savings / capital costs of the different options against typical conventional supermarket technology.

Keywords : Supermarkets, absorption cooling, combined heat & power, CHP, food refrigeration, CCHP

1.0 Introduction

This paper concerns the subject of cogeneration or combined cooling, heating and power (CCHP). The paper specifically uses a refrigeration application, the supermarket to introduce the technology suitable for lower temperature CCHP. The paper then defines the cooling, heating and power requirements of the supermarket. It describes a model that has been developed to investigate the CCHP options available. Finally, the paper describes the evaluation of these schemes and the results define their economic and environmental viability compared to conventional methods of providing cooling, heating, and power.

2.0 Background

In recent years, it is not uncommon to consider the use of Combined Heat and Power (CHP) schemes in commercial applications. With the Kyoto agreement, there has been a greater emphasis on reducing energy use and on considering energy efficient systems such as CHP. As a result, the installation of new CHP systems to displace less efficient means of power generation, is now an important part of the UK strategy to reduce greenhouse gas emissions by 20% by 2010 [1].

A CHP or cogeneration system consists of the facility simultaneously to produce and use heat and power. Gas engines or turbines generate power via their electric generators (alternators) and the by-product energy from the exhaust gases, jacket water, inter-coolers, oil coolers, etc, is used for heating.

CHP schemes are usually more efficient than conventional coal fired power stations as they produce electricity locally, minimising the distribution losses, and they use the heat from the CHP plant for space or process heating. In addition to the running cost savings associated with higher efficiency, the lower energy consumption also produces environmental benefits, since non-renewable energy reserves are preserved and environmental pollution is reduced. As a result a CHP scheme will be exempted from the UK Climate Change Levy on gas and electric energy, when it is enacted in April 2001, providing users can justify that their CHP system is efficient and uses the heat and power provided simultaneously [2].

CHP schemes have been applied for over 100 years and have been used to provide electric power from 15kWe to 100MWe. In most applications the main factor which determines the economic viability of the CHP scheme is a high utilisation of the heat and power which are produced simultaneously. Most of the literature indicates that the CHP plant needs to be fully utilised providing heat and power for a period of at least 4500 hours per annum, to be viable (4 to 5 years payback period) [3]. The main difficulty in achieving high annual utilisation is providing a heat demand during the summer months.

CHP has been applied to two supermarket applications in the UK. Sainsbury's used CHP at their Greenwich store to produce electricity locally on site and to provide hot water for heating and toilet/ canteen facilities [4]. Safeway employed an "Air CHP" package at their Milton Keynes store [5]. This used heat generated by the engine to warm air directly within an air handling unit. This scheme was reported to give a 5% increase in generation efficiency compared to conventional CHP [6].

To achieve high utilisation this plant was operated continuously throughout the year and this was achieved during periods of low heat demand by rejecting excess heat to atmosphere. Adopting this 'electricity led' control scheme enabled the CHP unit to offer a reported payback period of 4.5 years. Calculations showed that in order to achieve this payback period significant heat rejection was necessary. As a result the CO_2 emissions

/primary energy used by this scheme are not significantly different to that from a conventional supermarket, even though the energy cost was significantly lower. It is also unlikely that the scheme would qualify for the Climate Change Levy (CCL) exemption under the CHP Quality Assurance Programme.

A summer demand for the heat generated by a CHP package can be provided if the system is integrated with an absorption cooling system. Heat from the CHP unit can be used to power the absorption chiller which can provide cooling for the chilled food cabinets and indirectly for the store itself.

CCHP schemes consist of a combination of absorption refrigeration and engines or turbines with their respective electric generators [7, 8, 9]. Further information on the application of absorption chillers to CHP systems is available [10, 11, 12]. The main CCHP systems found on the market are:

a) Gas Turbine - electric generator, double-effect steam-driven absorption chiller:
The exhaust gas heat of the gas turbines is used to drive absorption chillers indirectly by means of an exhaust gas to steam heat recovery boiler. These systems are normally very large scale and well above 1MWe, which is where gas turbines are normally more competitive than gas engines.
b) Gas Engine - electric generator, single-effect hot-water driven absorption chiller:
Gas engines have two sources of waste heat: the exhaust gases and the jacket cooling water. Both of these are used to drive a single-effect absorption chiller.

Combined Cooling, Heat and Power (CCHP) schemes have been used in many applications including dairies, food processing, cold storage and pharmaceutical facilities, as well as more conventional air conditioning applications. CCHP has not been reported in supermarket applications and this paper describes the investigation into the use of CCHP in these applications.

3.0 Methodology
This paper investigates a number of CCHP schemes compared to the traditional supermarket. The criteria used to compare the viability of the different systems are energy costs, capital costs and primary energy usage. These have been determined using a purposely developed mathematical model of the typical supermarket that is described below:-

3.1 The Typical Supermarket
A specimen supermarket of approximately 5000m^2 trading area has been used in this investigation. This size was chosen as it is slightly larger than average [13]. The supermarket has two floors. The ground floor includes the retail area, cold stores, food preparation/ processing areas, dry stores and a restaurant. The store is assumed to be open from 7am to 10 pm, 7 days a week.

The heating, cooling and power requirements of the supermarket are defined below:-

3.11 Heat demand
The thermal loads found in the supermarket are: conduction through the building fabric, occupancy, lighting, thermal spill from the refrigeration cabinets, infiltration and fresh air, hot water, preheat loads.

The peak sensible heat loads calculated for the supermarket are shown in Table 1.

To satisfy these heat demands, a mechanical warm air ventilation system is traditionally employed. A gas fired boiler provides hot water for the air handling unit. Because the cabinets produce a large cooling effect, most supermarkets do not utilise either sensible or latent air-cooling. Despite this, the supermarket is assumed to operate close to the design condition of 21^{o}C throughout the trading period throughout the year. To save energy the supermarket thermostat is set back at night to 16^{o}C.

3.12 Cooling Demand
The cooling demand for the supermarket is shown in Table 2.

The refrigeration systems currently installed in the supermarket are centralised systems. The food is grouped by product temperature into chilled (High Temperature: HT) and frozen (Low Temperature: LT) food categories. The refrigeration system used for both chilled and frozen food cabinets is detailed in Figure 1, which shows dedicated compressor packs operating on separate suction lines with common delivery headers. Normally to minimise the risk of failure there are two independent central systems, each designed to meet 50% of the cooling load. The compressors used in each system are mounted on a base plate to form a compressor pack, which also includes a liquid receiver and multi-station manifolds for individual liquid, suction and defrost gas connections. Compressor motors are speed controlled to match load variations.

The operating conditions of the screw compressor used are shown in Table 2. The day cabinet loads are also shown in Table 2 and these are assumed constant throughout the trading period, since, the internal supermarket environment is maintained. At night, the load is reduced to 70% of the day value with the use of night blinds [14].

3.13 Electrical Demand
The electrical loads found in the supermarket are: lighting, fans, equipment and refrigeration plant. The total electrical usage by the supermarket is shown in Table 3.

3.2 Energy Model
The annual energy consumed by the typical supermarket was determined using a purposely developed mathematical spreadsheet model. The model uses the BIN method to calculate the hourly steady state energy consumption based upon average external dry bulb temperatures, for every single day of the year. These

calculations were modified to include non steady state effects such as energy storage in the building fabric during night setback and preheat. A time constant approach was used in analysing non-steady state heat transfer. The hourly energy consumption figures were summed to give annual usage. Annual energy costs were determined using the tariffs shown in Table 4. Only the CCHP scheme is exempt from the Climate Change Levy.

3.3 Model Validation

The annual energy consumption and cost calculated for the conventional supermarket is shown in Table 5. Table 5 also shows the primary energy consumed by a supermarket assuming electricity derived from a coal fired power station. This is initially used as the benchmark for establishing primary energy savings for CHP and CCHP schemes [1]

The output of the mathematical model has been compared against typical data reported in the literature. The results of the comparison are detailed in Table 6. This shows that the model predicts accurately the energy cost per unit area as well as energy consumption. The model does give a lower ratio of electricity to fossil fuel consumption than that given by both Sainsbury's [15] and the BRE [13]. It is considered that this may be due to the small proportion of frozen food cabinets used in this supermarket. The ratio of chilled to frozen food used is less than 4:1. The model is therefore considered suitably valid for carrying out feasibility studies.

4.0 Investigations

4.1 CCHP Schemes Considered

Conventional CCHP systems are applied to air conditioning applications and provide chilled water at around 7°C. However, supermarkets require lower and different requirements, one for the chilled cabinets (HT) and another for the freezer cabinets (LT).

For reliability purposes, supermarkets typically have two independent central systems each sized for 50% of the total capacity. Upon the failure of one system, the business is able to survive in part without significant losses. However it would not be able to survive if the entire refrigeration system failed, which given two independent systems is much more unlikely to occur. In theory the probability of failure of two events is the square of the failure of one event [16]. Therefore, the design of the CCHP systems applied to supermarkets has followed this design philosophy, to meet the loads of one half the supermarket's refrigeration capacity. Maintenance and reliability of CCHP compared to the traditional supermarket has not been considered in detail in this paper and will be subject of later work. There are, however, arguments in favour of CCHP, as well as arguments against.

The size of the supermarket in question, the need to have two refrigeration systems, and the split between the low and high temperature cabinets, requires CHP systems well below 1MWe (CHP electric power), which excludes gas turbine type systems. The implication of this is that it excludes achieving temperatures required for frozen food using an absorption chiller, because it would need a heat source temperature from the CHP plant in excess of 180°C. This can only be achieved by gas turbines, and not by gas engines. Micro gas turbines were not considered in this study as they are a relatively new and expensive technology. Given that the capital costs of the CHP plant critical, this study has considered only low cost gas engines, with proven market penetration. This does not mean that micro-turbines cannot be considered in the future.

The array of possible sorption chillers is quite varied. Five options were considered; all are cooled with dry coolers assisted with water spray for peak summer conditions. Using the BIN model the economics and environmental performance of these schemes were investigated. The salient characteristics of the schemes considered are shown in Table 7.

In all schemes, the absorption chiller has been sized to satisfy the cooling load for half the supermarket only. Cooling for the remaining half of the supermarket is provided by conventional vapour compression refrigeration. In schemes 1 and 2, the absorber chills propylene glycol which is circulated to the chill cabinets where it provides cooling. The major difference between schemes 1 and 2 is that the absorption chiller is used to provide chilled glycol. Whereas scheme 1 requires a higher temperature CHP engine to power the absorption chiller.

Schemes 3, 4 and 5 use the absorption unit to chill water which is then circulated to the chilled and frozen food display cabinets. These incorporate a cascade vapour compression system and the chilled water provides cooling for the cascade condenser. The main difference between these schemes is the chiller unit used.

Each CCHP scheme was assumed to be controlled using a heat led strategy. Although, there are a number of ways of controlling CHP output, heat led control was used because it maximises primary energy savings. A heat led strategy enables the engine to modulate to always satisfy heat demand. As all schemes incorporated a parallel type generator synchronised with the mains, the balance between electricity demand and CHP unit output can be maintained with the export or import of power.

With the exception of option 3, all the sorption machines have been developed, with proven prototypes, but have only achieved to date a very low market penetration. This has an effect on their capital costs, which are not so competitive as the standard LiBr/water chiller of option 3.

4.2 Results

In each case the annual energy consumption and costs were calculated using the model and this has been compared against that calculated for the traditional system. The additional capital and maintenance costs associated with the CCHP schemes have been calculated and the viability of each case has been considered in terms of payback period and primary energy saved. The cost tariffs used for the CCHP schemes are shown in Table 4.

Each scheme was modelled across a range of CHP capacities and results were compared using payback period and primary energy savings. The model found that both these factors were highly sensitive to the engine size selected. This is shown in Figure 2. Investigations identified that the results were better represented against another factor 'EFLH' instead of engine size. EFLH is equivalent full load hours of simultaneous heat and power for the CHP system used, and this varies with engine capacity. Higher engine sizes will run at part load for longer periods and therefore will have lower equivalent full load hours.
The results from the investigations in terms of payback period and primary energy saving against equivalent full load hours are shown in Figures 3 & 4. From these Figures it can be seen that the shape of the curves is similar for all schemes.

The general conclusion that can be derived from Figure 3 is that all schemes produce the lowest payback period at approximately 7500 EFLH. Although higher revenue cost and energy savings are achieved at lower equivalent full load hours, larger engines are required and this increases capital costs. 7000 to 7500 EFLH therefore represents the best compromise between revenue and first costs. Option 3 can be seen to produce the lowest payback period although the scheme does not give the lowest primary energy consumption or energy cost. The main reason for option 3 being more competitive is that it uses a conventional Lithium Bromide chiller which are available at lower costs due to their established market penetration in air conditioning applications.

Figure 4 shows that primary energy consumption against equivalent full load hours. This shows primary energy consumption is lowest when equivalent full load hours are low. This is because the control regime used requires larger engine capacity to achieve lower equivalent full load hours. Higher primary energy savings occur with larger engines as more energy is being generated by the CHP unit and this is more efficient in terms of primary energy consumption than coal derived electricity and boiler heat. At high equivalent full load hours the engine capacity used is small and a gas boiler is used to supplement the heat required to power the absorber.

If the primary energy consumption is compared with electricity produced by more efficient power stations then the CCHP schemes do not produce significant primary energy savings. This is detailed in Figure 5, where the primary energy savings are shown against for more efficient CCGT (Combined Cycle Gas Turbine) generation. Compared to CCGT generation, the CCHP uses approximately the same primary energy consumption. This suggests that the exegetic efficiency of the CCHP scheme is similar to that of conventional power and heat generation in the supermarket, supplied with efficient power stations (i.e. CCGT).

From Figure 4 it can be seen that the primary energy profiles for schemes 1 and 2 are similar. Option 2 produced the lowest primary energy, and this is primarily a result of the slightly better efficiency of the option 2's CHP engine which had more impact than the notably lower absorption chiller COP. This indicates that generation efficiency is of more importance than the utilisation efficiency, under these conditions. Primary energy savings for options 3, 4, and 5 are approximately 3% less than those calculated for options 1 and 2. This reduction is mainly due to the inefficiency caused by the additional heat transfer stage of the cascade system (cabinet compressor to chilled condenser water).

4.3 Discussion of Results
Based on the results, it is recommended to select CHP systems on 7000-7500 hours of simultaneous production of full load heat and power, in order to achieve primary energy savings of over 15%, whilst also achieving attractive paybacks.

These primary energy savings assume that the electricity displaced is from a coal-fired power station. However, because CO_2 emissions from gas derived energy are approximately 60% of emissions from coal, CCHP schemes could reduce CO_2 emissions by approaching 50%. In the short to medium term such CCHP systems could offer the level of CO_2 emission reductions sought by the UK Government. Longer term CCHP will need to compete on an environmental basis with more efficient electricity generation such as CCGT power stations.

Emerging technology will benefit the application of CCHP in the medium to longer term. Specifically these include the mini gas turbine and the fuel cell.

1) Gas turbines - Several large companies including Volvo are developing mini-turbines for mass market consumption between 15 and 500 kWe output. As well as lower capital cost through economies of scale, in the future, these turbines offer reduced maintenance [17] and could be used to drive lower temperature absorption cooling schemes suitable for freezer duties.

2) Fuel cells are receiving significant development and could be used in place of the engine in a CHP package. The advantage of fuel cells over a conventional engine is that they offer a 10% increase in electrical generation efficiency and they produce virtually zero pollution. [18]. Currently one of the main market barriers of the fuel cell is its cost, which is approximately $3000/ kWe capacity. This is at least 6 times more expensive than a conventional gas engine.

5.0 Conclusions
This paper describes the theoretical analysis of CCHP schemes applied to a supermarket. Although the work is

based on a case study of a supermarket, the results are relevant to other refrigeration applications that have relatively constant loads, such as cold storage, processing or industrial refrigeration applications. The paper describes a validated mathematical model that has been developed and used to accurately predict the energy performance of the supermarket. Important heating loads due to cabinet spillage were noted, even during the summer season. The opportunities are significant for energy savings in this field.

The model has been used to investigate five CCHP schemes whereby the optimum one uses a standard Lithium Bromide absorption chiller. The main reason for this is the low cost of the LiBr absorption chiller itself. This option offers a payback period under 7 years. There is a potential to save capital costs on the new technology sorption chillers with serial production and economies of scale, which would reduce the payback periods of the other options. This would be possible with widespread use and standardised supermarket M&E services design.

The results indicate that in the short to medium term CCHP could offer significant primary energy/ CO_2 savings compared to conventional heat and power schemes based upon a gas boiler and coal derived electricity. In the longer term CCHP will have to compete against more efficient grid generated electricity. Current technology would not offer significant primary energy savings compared with improved grid efficiencies. However, emerging technology such as the fuel cell could offer CCHP, much improved engine efficiencies, which may give CCHP a long-term future in refrigeration.

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Table 1. Breakdown of the peak heat loads on the supermarket

Heat load	Day-time peak load kW	Night-time peak load kW
Conductive load	-110	-88
People Sensible load	+50	0
Lighting load	+194	0
Cabinet load	-264	-154
Infiltration load	-208	-167
Fresh air load	-122	-97.9
Fan heat	+50	+50
Hot water load	-10	0
Total steady state load	-420	-507

Table 2. Refrigeration system specification

System	Compressor pack	Day cooling load kW	Night cooling load kW	Peak Saturated Delivery Temperature °C	Minimum Saturated Delivery Temperature °C	Saturated Suction Temperature °C
1	HT1	225	158	45	25	-12
	LT1	52	36			-36
2	HT2	225	158			-12
	LT2	52	36			-36

Table 3. Breakdown of the electricity use by the supermarket

Electrical load	Day-time peak load kW	Night-time peak load kW
Lighting	260	20
Fans	50	50
Equipment	139	57
Refrigeration	446	253
Total load	873	358

Table 4. Utility costs

	Conventional Supermarket	CCHP Scheme
Gas cost	£0.011 /kWh Includes seasonal usage tariff and CCL	£0.009/kWh Continuous usage tariff
Electricity day time cost	£0.0493 /kWh Includes CCL	£0.045/kWh
Electricity night time cost	£0.0273/kWh Includes CCL	£0.023/kWh
Electricity export price	-	£0.018/kWh
CHP - Maintenance cost	-	£0.006 /kWeh

Table 5. Predicted performance of the supermarket

	Model prediction–traditional supermarket
Annual Gas Consumption (kWh)	1,672,099
Annual Gas cost (£) (including CCL)	£18,393
Annual Electricity Consumption (kWh)	4,650, 739
Annual Electricity Cost (£) (incl CCL)	£214,351
Primary energy consumption (kWh)	13,910,887
Total energy cost (£) (including CCL)	£232,744

Table 6. Comparison of model's performance with other supermarket energy data

Criteria	Model Prediction	Sainsbury's Average 1994/ 95	BRE Typical
Energy cost £/m2 per year	46.5	47	-
Energy Use kWh/m2 / year	1265	1172	1254
Ratio of electricity to fossil fuel use	2.86	4	3-5

Table 7. Salient characteristics of CCHP Schemes

Opt	Absorption chiller	Chiller COP	Medium cooled	Medium temperature °C	Chilled food refrigeration	Frozen food refrigeration	Gas engine	Engine efficiency	Water temperature °C
1	Single effect NH3/ water	0.58	Propylene glycol	-8 to –4	Using cold glycol	Conventional – vapour compression	High temperature	46%t / 32%e	124
2	NH3/ water double stage	0.4	Propylene glycol	-8 to –4	Using cold glycol	Conventional – vapour compression	Conventional	57%t / 33%e	90
3	Single effect LiBr/ water	0.71	Water	7°C to 14	Cascade vapour compression system in cabinet	Cascade vapour compression system in cabinet	Conventional	57%t / 33%e	90
4	Single effect low temperature LiBr / H_20	0.62	Water	7°C to 14	Cascade vapour compression system in cabinet	Cascade vapour compression system in cabinet	Low temperature	59%t / 33%e	70
5	Silica Gel/ water *ad*sorption	0.6	Water	7°C to 14	Cascade vapour compression system in cabinet	Cascade vapour compression system in cabinet	Conventional	58%t / 33%e	80

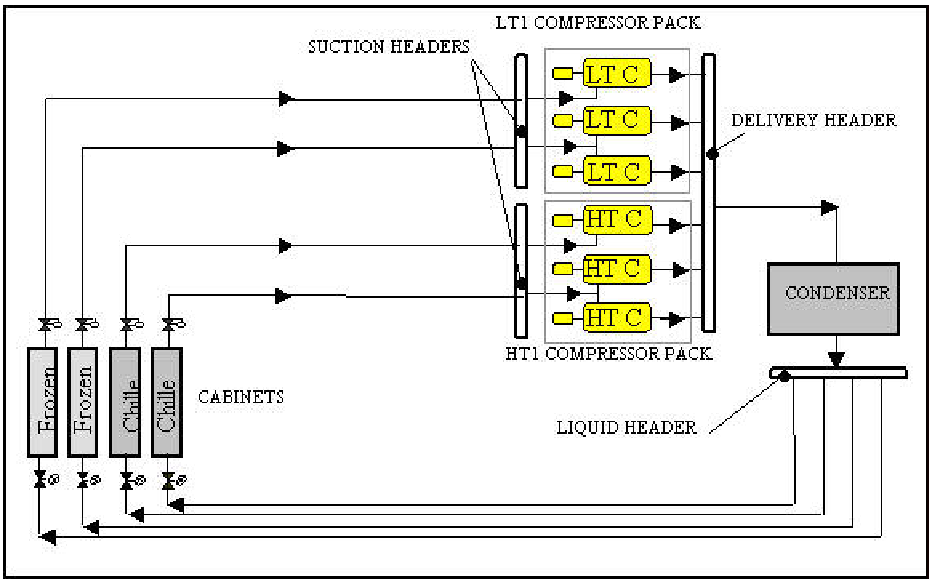

Figure 1. Schematic of typical refrigeration system used in the supermarket.

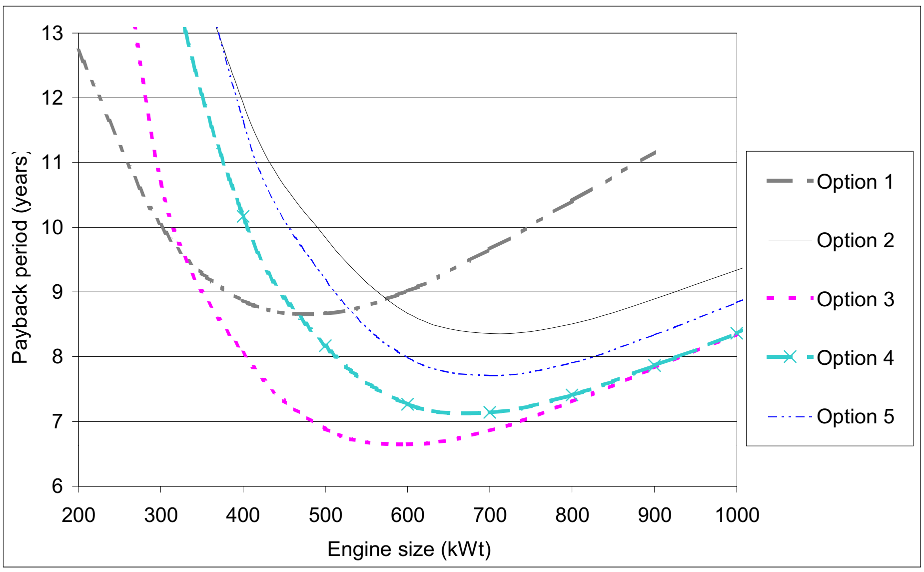

Figure 2. Graph of payback period saving against engine size

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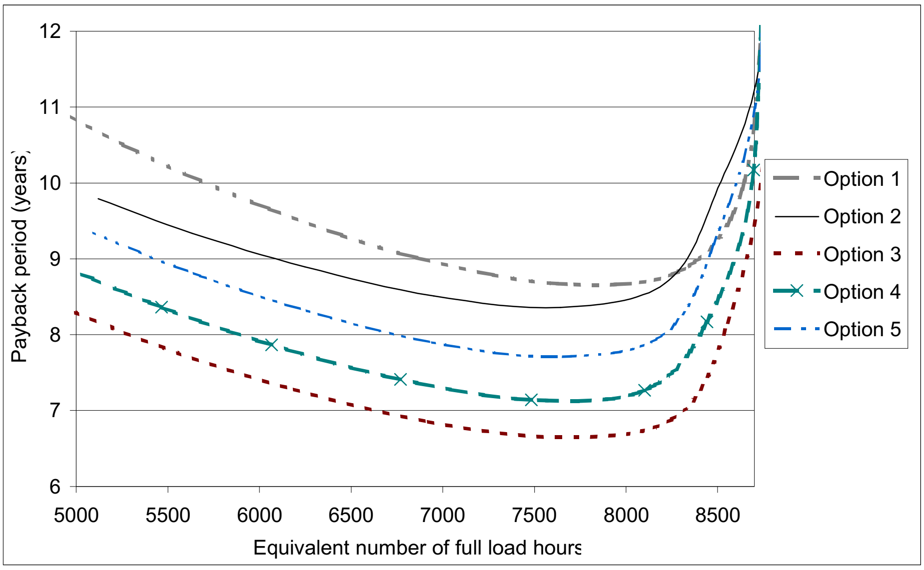

Figure 3 Graph of payback period against equivalent full load hours

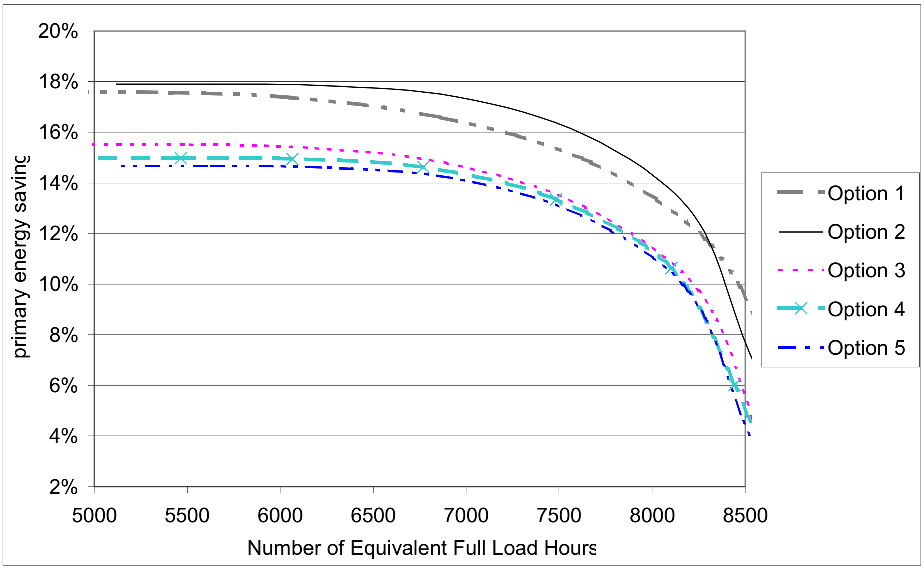

Figure 4 Graph of primary energy saving against equivalent full load hours

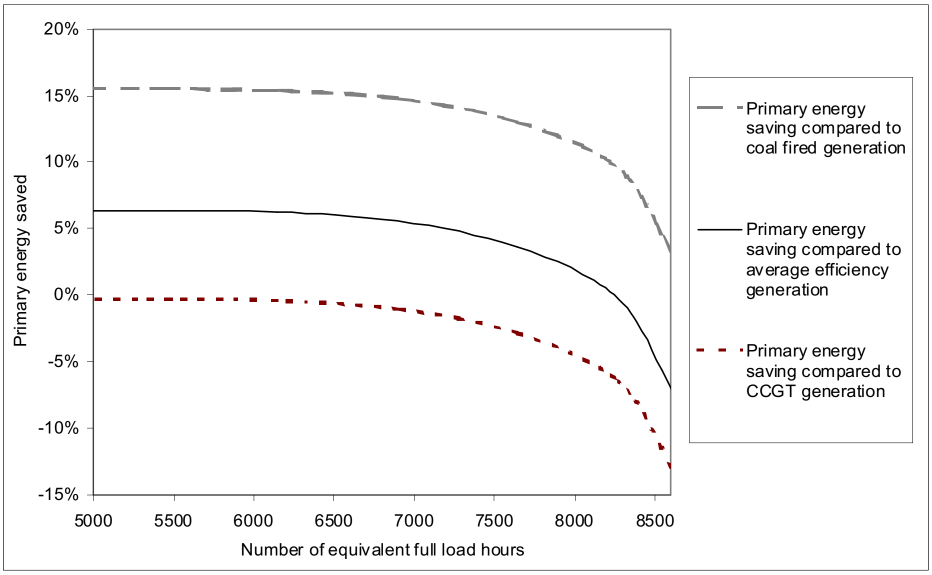

Figure 5 Graph of primary energy savings for option 3 against equivalent full load hours