THE INSTITUTE OF REFRIGERATION

TRIGENERATION – A SOLUTION TO EFFICIENT USE OF ENERGY IN THE FOOD INDUSTRY

by

S A Tassou*, D Marriott⁺, I Chaer⁺⁺, N Sugiartha*, N Suamir*

*Brunel University, Uxbridge, Middlesex UB8 3PH
+ Doug Marriott Associates
++ South Bank University

(Session 2007-2008)

To be presented before the Institute of Refrigeration at the Institute of Marine Engineering, Science and Technology, 80 Coleman Street, London EC1 on 3rd April 2008 at 5.45pm

Summary

The food Industry, food manufacturing, storage and retail, has a need for heating and electrical power as well as refrigeration. Invariably, plant is installed which consists of heating systems employing low pressure hot water, high pressure hot water or steam, vapour compression refrigeration systems and an electrical power supply derived from the National Grid. The overall utilisation efficiency of these processes is low because of seasonal variations in demand and the relatively low electricity generation efficiency in power stations and distribution losses in the grid. One way of increasing the energy utilisation efficiency of food manufacturing, storage and retail facilities is through Combined Heating Refrigeration and Power (CHRP) or trigeneration. Trigeneration systems have been in operation for many years but only in a small number of food manufacturing industries. Recent increases in fuel prices, concerns about the environmental impacts of the food industry and developments in technology have increased interest in the application of trigeneration to the food industry.

This paper reviews the main technologies employed in trigeneration systems. The paper also outlines research, development and application challenges and explores the influence of the performance characteristics of trigeneration systems on energy performance and environmental impacts in supermarkets.

1. Introduction

In industrialised countries, the food industry constitutes one of the largest industrial manufacturing groups and is responsible for substantial energy consumption and greenhouse gas emissions. In the UK, the primary energy consumption for the food chain as a whole is estimated at 240 TWh. Of this, approximately 27% is for food and drink manufacturing, 21% for catering, 8% for agriculture, 5% for retail and 39% for domestic cooking and refrigeration. If one excludes the domestic energy and the energy consumed by agriculture the energy consumption by the food chain is around 126 TWh per year which represents 14% of energy consumption by UK businesses and contributes to around 30.0 $MtCO_2$ tonnes of carbon emissions per year (Defra, 2006).

In food manufacturing, approximately 68% of the energy is used by fuel fired boilers and direct heating systems for process and space heating. The remainder 32% is electrical energy used by electric motors (16%), electric heating (8%) refrigeration equipment (6%) and air compressors (2%) (AEA, 2007). The energy consumption by the food and drink manufacturing sector is estimated to contribute to 11.5 $MtCO_2$ emissions, made up of 6.9 $MtCO_2$ from fossil fuel use and 4.6 $MtCO_2$ from electricity (FDF, 2006).

The UK's Kyoto target is to reduce greenhouse gas emissions by 12.5% from 1990 levels within the commitment period of 2008-2012. The UK is on course to meet this target but is unlikely to meet the tougher self-imposed target to cut CO_2 emissions by 20% from 1990 levels by 2010. This target has now been superseded by new targets in a draft Climate Change Bill (HM Government, 2007). The Bill proposes to impose an interim target of 26–32% reduction in CO_2 emissions by 2020 alongside the 60% reduction by 2050. The Energy White Paper published in 2007 sets out a framework of measures to address these challenging targets (DTI, 2007).

The wider application of Combined Heat and Power systems (CHP) for distributed power generation is one of the key elements in the white paper. CHP is a potentially carbon-efficient technology which produces heat as a by-product of local electricity generation. The total CHP capacity in the UK in 2006 was 5549 MWe from 1539 schemes. It contributed 27973 GWh of electricity which represented 7.5% of total electricity generation in the UK (DUKES, 2006). CHP capacity of the UK food industry is reasonably good but there is scope for improvement. In 2002 this capacity was 404 MWe, generating 1953 GWh of electricity. The economic conditions for investing in CHP installations have not been very good in recent years because of high gas prices and low electricity prices. However, the Government remains committed to achieving a national target of 10 GWe of good quality CHP by 2010 and this implies an increase in CHP capacity in the food sector to 1.0 GWe. To achieve this target, further support measures were introduced in its 2004 CHP Strategy, and in the 2007 White Paper on Energy (DTI, 2007). These measures include:

- Exemption from the Climate Change Levy;
- Business Rates exemption;
- full reward for the carbon saving of CHP under the allocations for EU ETS (Emissions Trading Scheme) Phase II, which will inform HMGovernment's thinking for Phase III;
- Enhanced Capital Allowances for power stations and equipment; and
- Renewable Obligation Certificate (ROC) eligibility for the biomass element of fuel used in energy from waste plants that utilise CHP.

The energy and carbon savings from CHP installations can be as high as 30% compared to separate heat and power generation but this depends on many factors such as the size of the scheme and the nature of the heat load (DTI, 2007). For maximum savings there needs to be simultaneous demand of heat and electricity and a fairly constant heat demand throughout the year.

In many applications where the demand for heat does not remain constant throughout the year, the utilisation efficiency of a CHP plant can be increased if the excess heat is used to drive thermally driven (sorption) refrigeration systems. The integration of CHP with sorption refrigeration technologies is known as Combined Heating Refrigeration and Power (CHRP) or tri-generation.

Food waste in the UK is estimated to be 4.1 million tonnes from food manufacturing and 1.6 million tonnes from food retailing (Defra, 2007). The quantity and impact of food waste can be reduced through better business processes and management and its utilisation to generate power. One million tonnes of food waste can generate between 85 and 135 GWh of electricity if the material is digested and the gas produced is used to drive CHP or trigeneration systems. This process is also known as Polygeneration. The electricity and heating and/or cooling generated can be used to satisfy part of the energy requirements of the food processing facilities, Regional Distribution Centres (RDCs), or cold stores.

A number of studies and projects have been performed on the application of trigeneration in the food industry. Bassols *et.al* (2002) presented several examples of this. In these applications, a range of prime movers were employed in conjunction with ammonia-water refrigeration systems.

Maidment *et.al.* (1999) considered the feasibility of application of CHP in a supermarket. The investigators found the system to be viable, with a projected payback period of approximately 4 years. Because of the low heat demand for space heating in the summer months, however, it was found that considerable amounts of heat would be rejected to the atmosphere. To improve the utilisation the authors also considered the feasibility of using the waste heat to drive an absorption chiller to provide refrigeration at -10°C for secondary refrigeration chilled food display cabinets. It was concluded that such a system is feasible and would lead to a payback period of 5 years.

Maidment and Prosser (2000) also considered the application of CHP and absorption refrigeration systems to cold storage facilities. Different system configurations were investigated and the feasibility results indicated a payback period of approximately 4 years.

A project funded by the European Union, 'OPTIPOLYGEN' considered the application of polygeneration to the food industry. The aim of the project was to investigate the application of polygeneration and to develop tools, data and guidelines to promote its application. (OPTIPOLYGEN, 2006). The results of the project indicated that with suitable policy measures, in the EUR-15 countries that were considered in the study, the potential for electricity generation from CHP in the food industry was 40 TWhe, from tri-generation applications 15 TWhe, and 16 TWhe from the use of biomass or biogas electricity generation. According to the study, 70%- 80% of the energy needs of the food industry could be satisfied by polygeneration but at present only 25% of this potential is exploited. The study also identified a number of technology gaps that need to be addressed in order to accelerate the application of polygeneration technologies in the food industry. These include:

- Improvement of the electricity generation efficiency of CHP systems,
- Improvement of efficiency of absorption refrigeration systems.
- Increase of electricity to heat ratio of commercially available CHP systems.
- Development of off the shelf (packaged) systems to simplify integration and reduce capital cost.
- Reduction in capacity and footprint of commercially available biogas plants.
- Development and application of fuel independent technologies such as Stirling engines.

Work at Brunel University in recent years has investigated the practical application of tri-generation systems in the retail food industry to provide electrical power for the supermarket and refrigeration for chilled food display cabinets. The work which is funded by Defra and is supported by food retail and refrigeration companies has lead to:

- The development of tools for the evaluation of the economic and environmental performance of Combined Heat, Power and Refrigeration schemes (Tasou et.al, 2007; Sugiartha et. al. 2006),
- The establishment of test facilities in the University for the testing of systems and evaluation of components with electricity generation capacities up to 100 KWe,
- The establishment of the performance characteristics of microturbine based tri-generation systems for medium temperature retail food refrigeration applications and optimum integration of components.

A current project funded by Defra is investigating the integration of tri-generation and CO_2 refrigeration systems for retail and other food engineering applications.

Increases in energy prices and pressures to reduce the energy consumption, waste and environmental impacts of the food industry, has increased interest in the application of CHP and trigeneration in both the food retail and food manufacturing sectors in the UK. This paper provides a review of the state of the art in trigeneration technologies and details results of research and development work in Brunel University. The objective is to increase awareness of the potential of the technology and provide information that will be useful in the selection of systems for specific food industry applications.

2. Trigeneration Technologies

A trigeneration system is normally an integration of two major technologies: the CHP system and a thermally driven refrigeration technology. CHP systems, many of which are available in packaged form, consist of a prime mover which drives a generator to produce electrical power and a heat recovery system that recovers heat from the exhaust gases and the engine cooling water in the case of internal combustion engine based prime movers. A schematic diagram of a trigeneration system is shown in Figure 1.

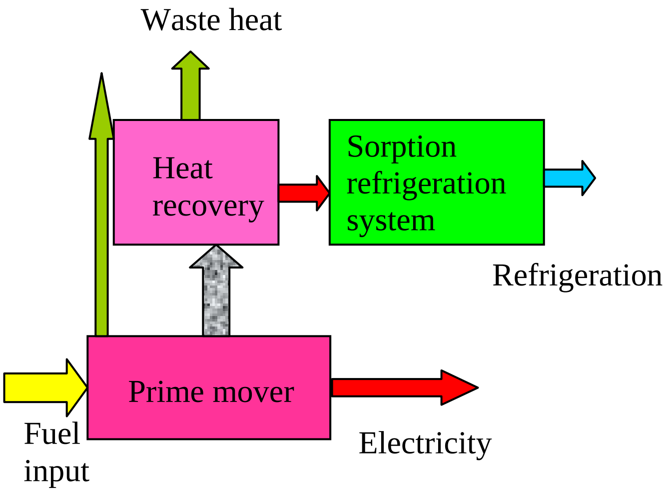


Figure 1: Schematic of a trigeneration system.

The following CHP technologies are currently in widespread use.

- Steam turbines
- Gas turbines
- Combined Cycle systems (gas and steam turbines)
- Internal combustion engines (Diesel and Otto).

These technologies are readily available, and fairly mature, and reliable.

Three other technologies have recently appeared on the market.

- Microturbines
- Fuel cells
- Stirling engines.

Table 1 details the main characteristics of these technologies, all of which can use either gaseous or liquid fuels.

The following sections provide more information on the three newer technologies.

Table 1: Characteristics of CHP systems

Technology	Size MWe	Electrical Efficiency (%)	Overall Efficiency (%)	Average Capital Cost (£/kWe)	Average Maintenance Cost (£/kWh)
Steam Turbine	>50	7-20	60-80	450-900	0.0013
Gas Turbine	0.5 - 25	25-42	65-87	200-450	0.002-0.005
Combined Cycle	>10	35-55	73-90	200-450	0.002-0.005
Diesel and Otto Engines	0.005 - 4.0	25-42	70-85	150-700	0.003-0.01
Microturbines	0.025 – 0.30	15-31	60-85	400-800	0.002-0.005
Fuel Cells	0.001 - 10	30-60	75-90	450-3800	<0.005
Stirling Engines	0.003- 0.1	40	65-85	2000	**?**

2.1 Microturbines

Microturbines are a new type of combustion turbine suitable for use in distributed energy generation applications. A schamtic of a microturbine power generation system is shown in Figure 1 and the major components of a commercial unit are illustrated in Figure 2.

Microturbine power generation units comprise a gas compressor, a combustion chamber, an air compressor, a turbine and an alternator. Compressed air is mixed with fuel and burned in the combustion chamber. The hot gases produced are expanded in a turbine which drives an alternator. Recuperated units recover heat from the turbine exhaust which is used to preheat the air entering the compressor. This improves the electrical generation of the unit but reduces the temperature of the exhaust gases and the amount of recoverable heat.

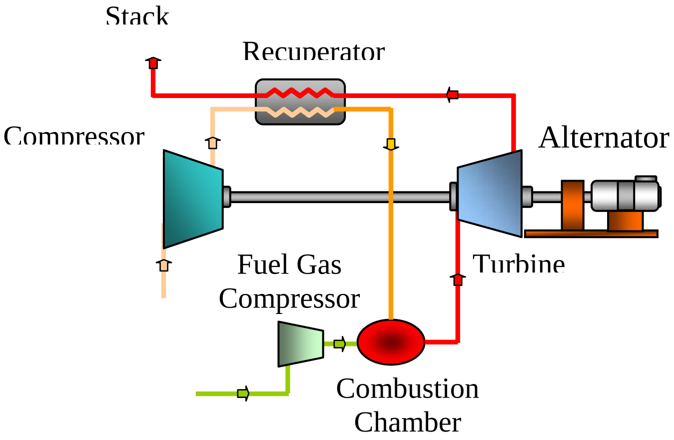


Figure 2: Schematic diagram of a microturbine.

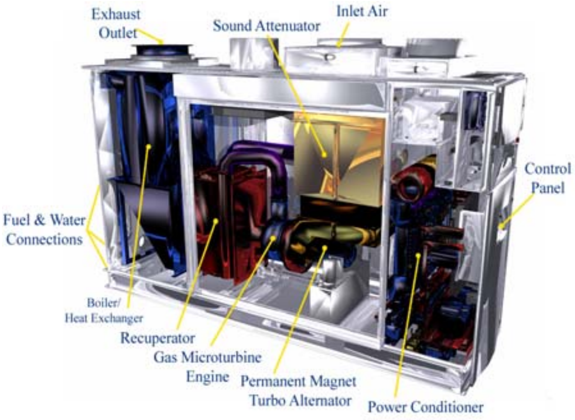


Figure 3: Bowman TG80RCG microturbine CHP system [12].

Microturbines offer advantages of compactness, higher exhaust gas temperatures and lower maintenance requirements than internal combustion engines. Their electrical generation efficiency, however, is lower than those of internal combustion engines.

2.2 Fuel Cells

A fuel cell is an electrochemical energy device that converts hydrogen (fuel) and oxygen (air) into electricity and heat. The hydrogen can be obtained from a variety of sources but the most common is through reforming of natural gas or other gaseous or liquid fuels.

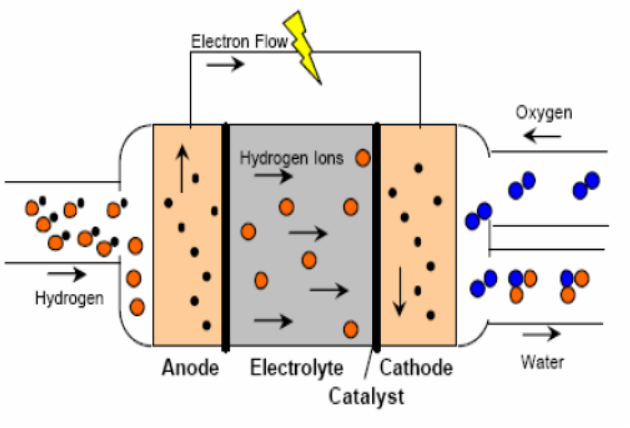


Figure 4: Principle of operation of fuel cell *(Fuel cell today, 2007)*

A fuel cell consists of two electrodes, an anode and a cathode, separated by an electrolyte. Power is produced when ions (charged particles) formed at one end of the electrodes with the aid of catalysts pass through the electrolyte. The current produced can be used for electricity. The electrolyte plays a key role as it must permit only the appropriate ions to pass between the anode and cathode. Passage of free electrons or other substances through the electrolyte, would disrupt the chemical reaction.

Fuel cells are categorized by the kind of electrolyte they use and include:

- Solid Oxide Fuel Cells (SOFC)
- Polymer Electrolyte Fuel Cell (PEFC)
- Proton Exchange Membrane Fuel Cell (PEMFC)
- Phosphoric Acid Fuel Cells (PAFC)
- Alkaline Fuel Cells (AFC)

The characteristics of these fuel cells are summarised in Table 2. Fuel cells have a typical electrical efficiency of between 30 and 60 % and an overall efficiency, if using the heat in a CHP arrangement of 70-90 %.

Apart from high electrical generation efficiencies, fuel cells offer advantages of low noise and greenhouse gas emissions and high reliability. Disadvantages include their relatively high cost, and short life span, typically 10 years. PAFCs are the most widely deployed fuel cells and more than 250 units of 200 kWe capacity have been installed worldwide since the early 1990s.

Table 2: Characteristics of fuel cells

Electrolyte	**Operating Temperature (°C)**	**Electrical Efficiency (%)**	**Typical Electrical Power (kW)**	**Fuel Type**	**Possible Applications**
AFC	60-90	40-60	20 kW	Pure hydrogen	Spacecraft, Submarines
PAFC	100-220	35-40	>50 kW	Pure hydrogen	Buses, trucks, large stationary applications
MCFC	550-700	45-60	>1.0 MW	Most hydrogen based fuels	Power Stations
PEFC/ PEMFC	80	30-35	<250 kW	Pure hydrogen	Passenger cars and mobile applications
SOFC	450-1000	45-65	>200 kW	Most hydrogen based fuels	Small to large stationary applications

2.3 Stirling Engines

The Stirling Engine is an emergent technology in the realm of CHP systems, despite the fact it has been invented in the 19th century. Combustion takes place outside the engine and the heat generated is used to heat the operating gas in the cylinder of the engine.

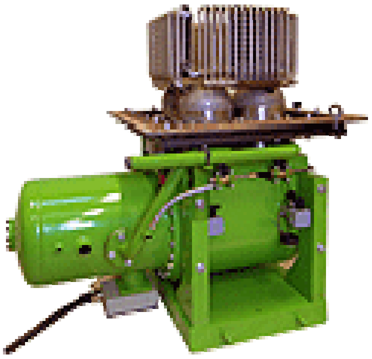


Figure 5: 35 kW Stirling engine (Stirling Danmark, 2007).

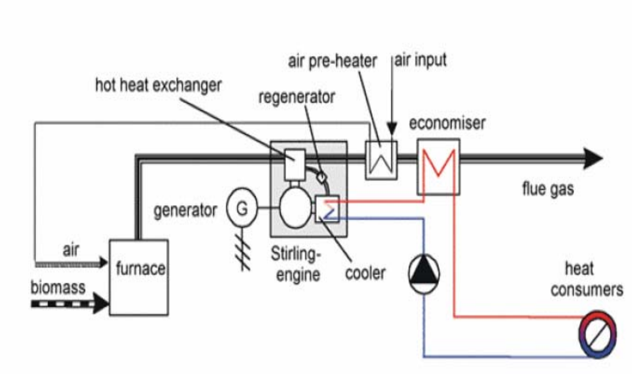


Figure 6: Schematic of a Stirling based CHP system (OPET, 2004).

The advantage of Stirling CHP systems over internal combustion based systems is that they can be powered by biomass, solar, and fossil fuels. This flexibility and the high efficiency of the engine offer significant potential for further development in the future.

2.4 Thermally Driven Refrigeration Technologies

The most common thermally driven refrigeration systems are based on the sorption technology where the mechanical compressor of the common vapour compression cycle is replaced by a 'thermal compressor' and a sorbent. The sorbent can be either solid in the case of adsorption systems or liquid for absorption systems. When the sorbent is heated, it desorbs the refrigerant vapour at the condenser pressure. The vapour is then liquefied in the condenser, flows through an expansion valve and enters the evaporator. When the sorbent is cooled, it reabsorbs vapour and thus maintains low pressure in the evaporator. The liquefied refrigerant in the evaporator absorbs heat from the refrigerated space and vaporises, producing the cooling effect.

2.4.1 Absorption Refrigeration Systems

The most common sorption technology is absorption refrigeration. Absorption refrigeration systems are characterised by the refrigerant fluid pair they use. The most common pairs are Lithium Bromide (refrigerant)-Water (absorbent) and Ammonia (refrigerant)-Water (absorbent). LiBr-H_2O water systems can only be used for cooling temperatures above 0°C. The technology is well established and packaged systems are readily available from a number of manufacturers in the USA, Japan, India and China which include Carrier, York, Sanyo, Hitachi, Yazaki, Thermax, Broad and many others.

Ammonia-water systems can provide refrigeration at temperatures down to -60°C. Commercial systems are available from only a very small number of manufacturers which include Colibri bv and Transparent Energy Systems. Robur supplies packaged systems able to provide 12 kW of refrigeration at brine flow temperatures down to – 12°C. A schematic diagram of a single stage ammonia-water system is shown in Figure 7.

The condenser, expansion valve and evaporator operate in exactly the same way as for the vapour compression system. In place of the compressor, however, the absorption system uses a number of other components: a generator, an absorber, a solution pump and a regenerating heat exchanger. A liquid solution weak in ammonia in the absorber absorbs ammonia vapour exiting the evaporator. The process is exothermic and so cooling is required to carry away the heat of absorption. The solution which becomes rich in ammonia is then pumped through a heat exchanger to the generator.

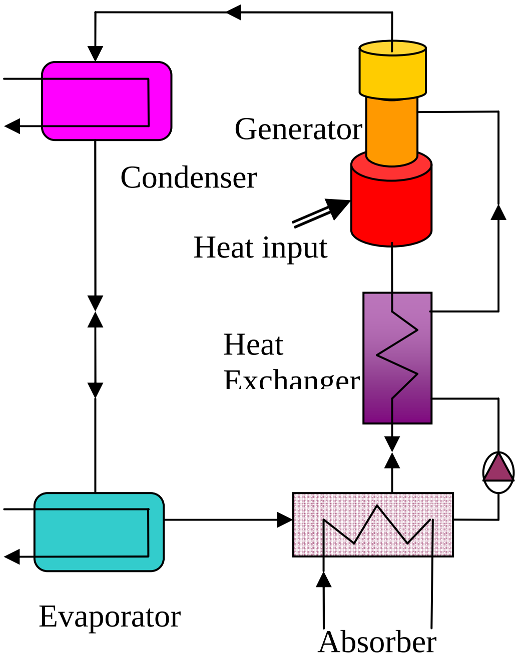


Figure 7: Schematic of Ammonia-Water absorption refrigeration system.

Heat supplied to the generator evaporates the ammonia from the solution. The solution which becomes weak in ammonia returns to the absorber through the regenerating heat exchanger where it preheats the solution supplied to the generator. The ammonia after passing through a rectifier where any water present in the refrigerant is removed travels to the condenser where it condenses by rejecting heat to a cooling medium. The ammonia liquid from the condenser flows through the expansion device before entering the evaporator where it evaporates and produces refrigeration.

Figure 8: Transparent Energy Systems PVT Ltd absorption refrigeration system (TES PVT Ltd, 2007).

Figure 8 shows an ammonia-water system employed in a trigeneration application in a dairy factory. The system provides 300 kW of refrigeration at a brine flow temperature of –5.0°C.

Figure 9 shows typical performance characteristics of ammonia-water absorption refrigeration systems. The refrigeration capacity and COP of the system is a function of the evaporating temperature, the temperature of heat input to the generator and the temperature of the condenser cooling medium. The COP of these systems will be 0.5-0.6 at evaporating temperature of -10°C and 0.25-0.4 at evaporating temperature of -50°C.

2.4.2 Adsoprtion Refrigeration Systems

Adsorption refrigeration unlike absorption and vapour compression systems, is an inherently cyclical process and multiple adsorbent beds are necessary to provide approximately continuous capacity. A schematic diagram of a simple adsorption system is shown in Figure 10. Adsorption systems inherently require large heat transfer surfaces to transfer heat to and from the adsorbent materials which automatically increases their size and cost.

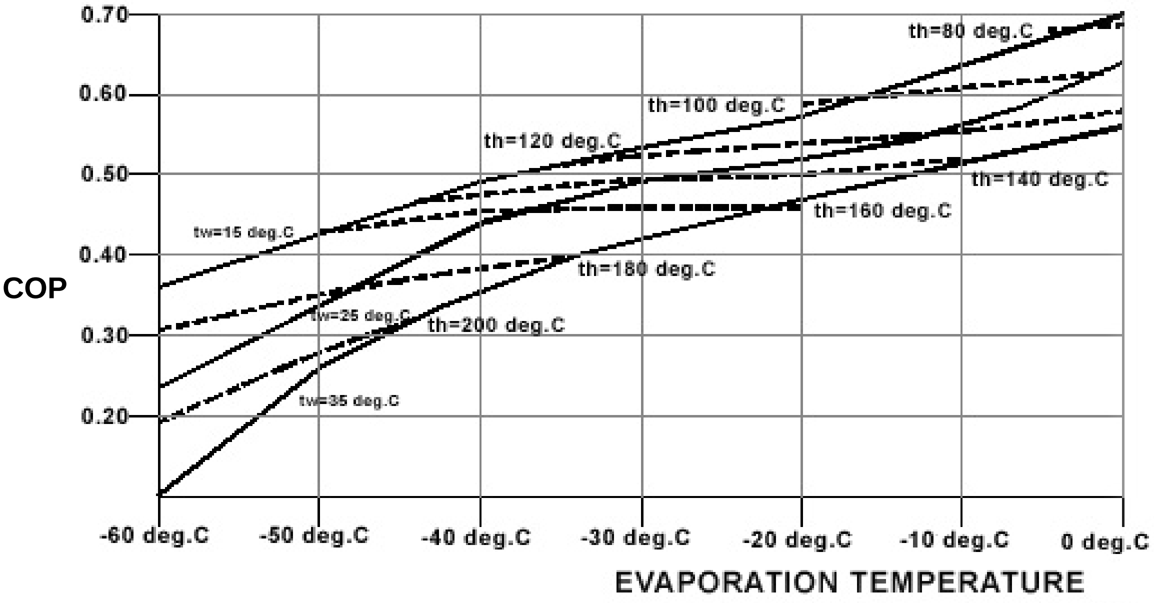


Figure 9: Performance characteristics of ammonia-water absorption refrigeration system (Transparent Energy System PVT ltd, 2007).

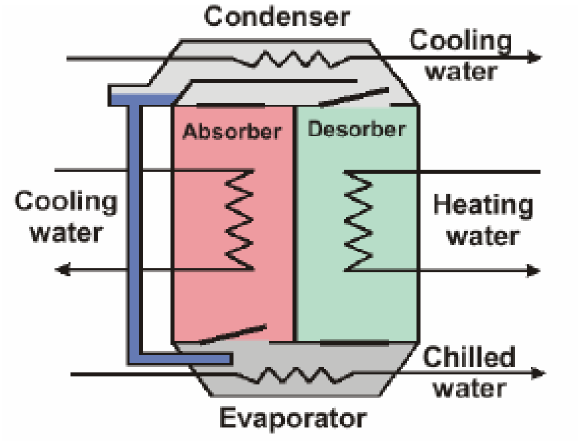


Figure 10: Schematic diagram of adsorption chiller (Bruno. et .al. 2007).

High efficiency systems require that heat of adsorption be recovered to provide part of the heat needed to regenerate the adsorbent. These regenerative cycles consequently need multiples of two-bed heat exchangers and complex heat transfer loops and controls to recover and use waste heat as the heat exchangers cycle between adsorbing and desorbing refrigerant.

Adsoprtion systems for air conditioning applications are already commercially available from a small number of manufacturers. "MYCOM", Mayekawa Mfg. Co., Ltd. are producing Silica-gel/water adsorption chiller (ADREF-models) with ranges between 35 and 350 kW for use in the air-conditioning industry. NISHIYODO KUCHOUKI CO. LTD, produce

Silica-Gel/Water adsorption chillers (ADCM models) with capacities between 70 kW and 1300 kW capable of being driven by low grade heat 50 – 90 °C and able to give COPs of around 0.65.

Figure 11: Nishiyodo adsorption chiller (HIJC Inc, 2007).

Research and development is also underway to produce systems for refrigeration applications and prototypes for temperatures down to – 25 °C are currently in operation.

3. Research and Development on Trigeneration Systems at Brunel University

The Centre for Energy and Built Environment Research (CEBER) at Brunel University has been involved in research on the development of trigeneration systems for food engineering applications since 2001. Research projects that have been funded by Defra and a number of companies in the retail food and refrigeration industries have resulted in the development of experimental test facilities and tools for the evaluation of the economic and environmental performance of trigeneration systems.

3.1 Experimental Test Facilities

The trigeneration test facility incorporates three main modules; CHP module, absorption refrigeration system module, and a refrigeration load module. A schematic diagram of the facility is shown in Figure 12.

3.1.1 CHP Module

The CHP module is based on a Bowman Power 80 kWe recuperated microturbine generation package (MTG80RC-G) with in-built boiler heat exchanger (exhaust heat recovery heat exchanger). The microturbine consists of a single stage radial compressor, single radial turbine within an annular combustor and a permanent magnet rotor (Alternator) all on the same rotor shaft. Other systems in the engine bay include the fuel management system and the lubrication/cooling (oil) system.

The fuel management system controls the gas (natural gas) supply, which is combusted in the burner to drive the turbine at constant speed of 68,000 rpm. During normal running, air for combustion of the gas is drawn-in from outside via a two stage filtration system, through the radial compressor where it is compressed and routed through the recuperator where it is preheated before entering the turbine burner (or combustor) stage, together with the fuel gas. The combusted gas powers the turbine, compressor and alternator. The electrical power output from the high speed alternator is fed to the power conditioner and switchgear circuits in the control and power electronics bay to produce 3-Phase electrical power output in the range 30 kWe to 80 kWe.

The fuel system comprises an external gas boost compressor which compresses the gas supplied to the combustor to 5.0 bar, and an internal fuel system that provides fine control of the gas fed to the burners.

Heat recovery from the exhaust gases is performed in a flue-gas/water heat exchanger. In the MTG80RC-G unit the heat exchanger consists of stainless steel coils imbedded in parallel flue gas streams to reduce pressure drop and the back pressure on the turbine.

Figure 13 shows the variation of the electrical generation efficiency and exhaust temperature of the microturbine CHP with power output. Maximum efficiency and exhaust gas temperature is obtained when the turbine delvers the maximum electrical power output of 80 kW.

3.1.2 Absorption Refrigeration Module

The refrigeration capacity of the test facility is depended on the type of thermally driven refrigeration system used. For ammonia-water refrigeration systems providing refrigeration at -10^{o}C, the unit is able to provide up to 50 kW of refrigeration.

The absorption refrigeration system currently employed, is a packaged gas fired ROBUR (ACF-60LB) chiller of specified refrigeration capacity of 12 kW at ambient temperature of 35^{o}C and chilled fluid (brine) inlet and outlet temperatures of 0^{o}C and –5^{o}C respectively.

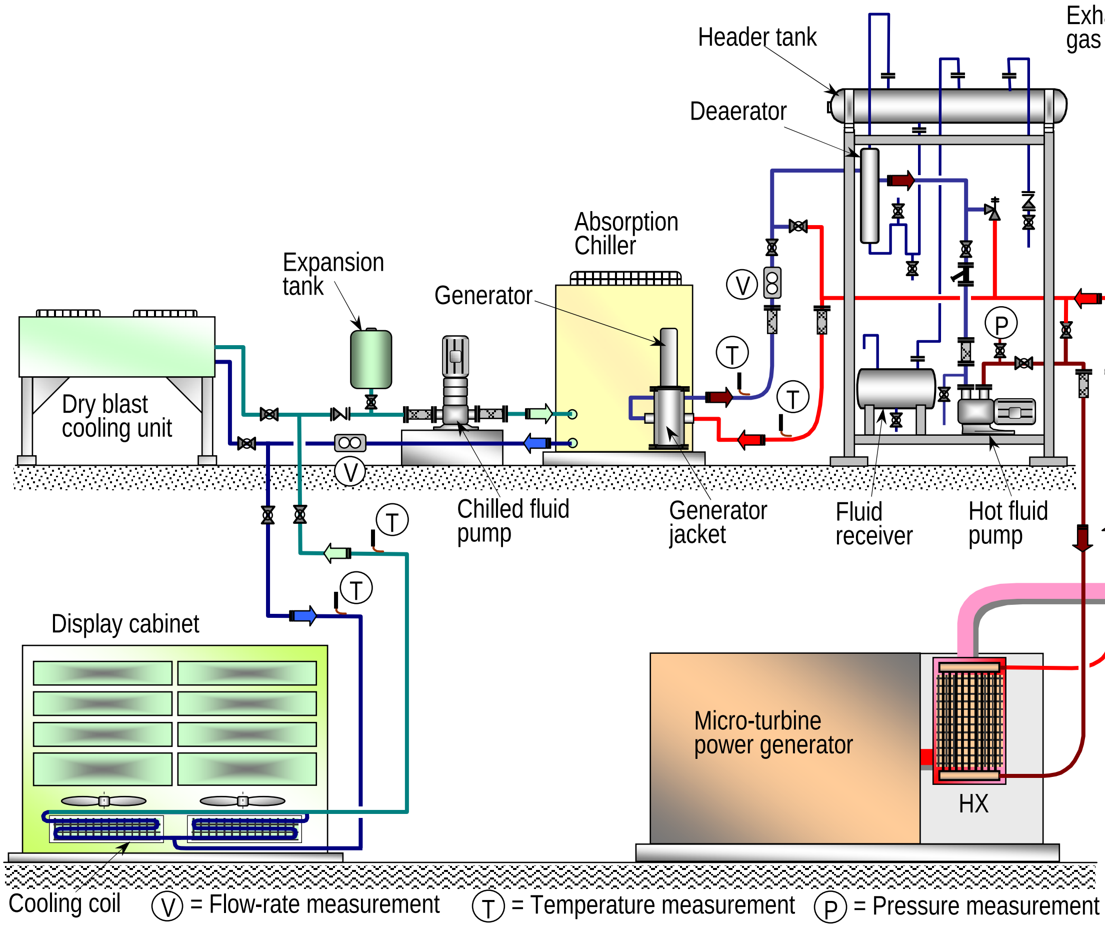


Figure 12: Schematic diagram of test facility using oil as the heat transfer medium between the microturbine and absorption refrigeration system.

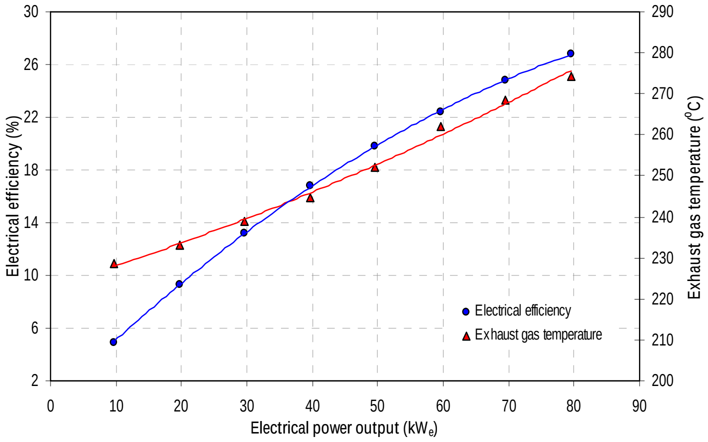


Figure 13: Variation of electrical efficiency and exhaust gas temperature with electrical power output.

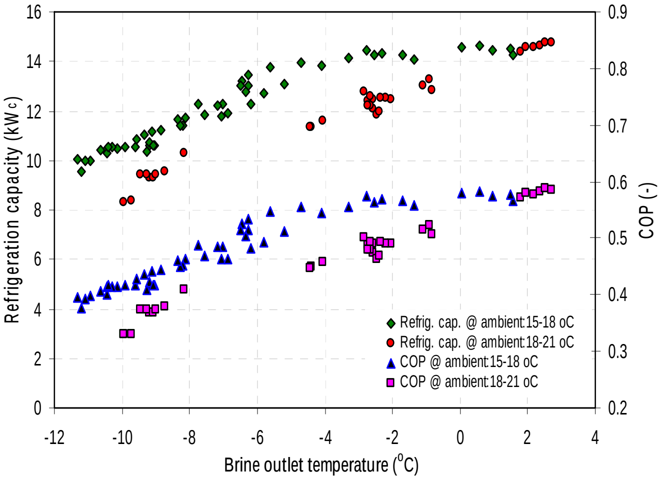
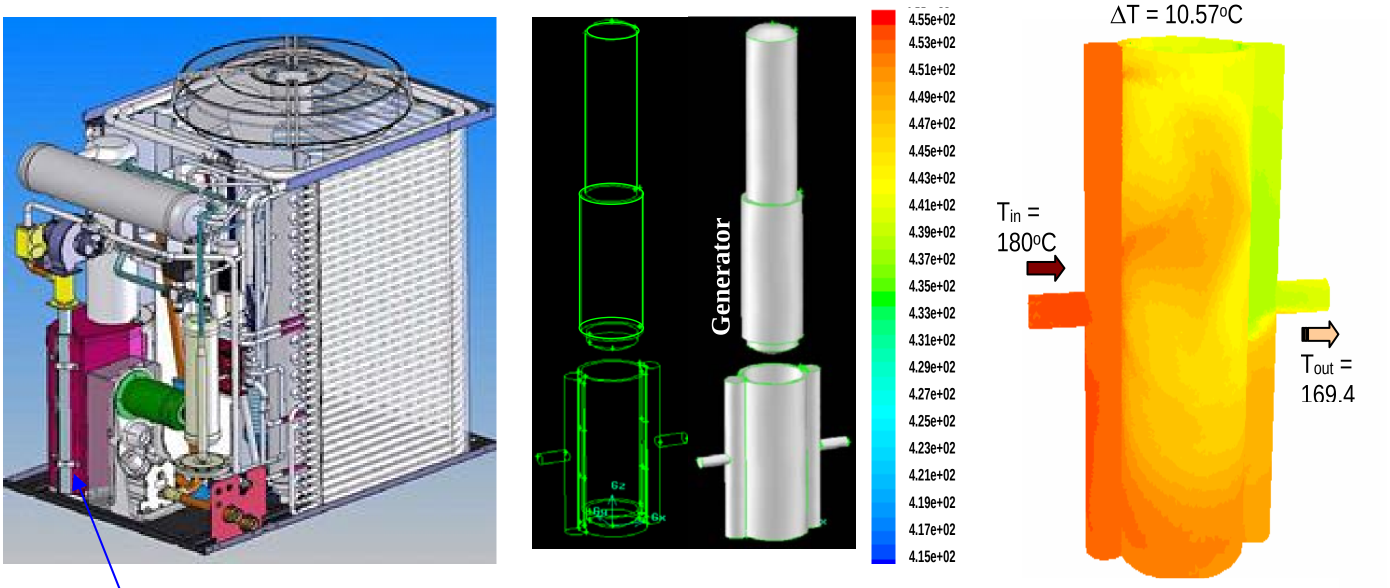


Figure 14: Refrigeration capacity and COP versus brine temperature for two ambient temperature ranges.



Original direct gas fired generator (Robur, 2006)

Modified generator with heat transfer fluid jacket

Design of of heat transfer jacket using CFD

Figure 15: Design modification of absorption refrigeration system to operate with heat recovered from the exhaust gases of the microturbine.

The performance of this unit, as established from tests in the laboratory is shown in Figure 14. For brine flow temperatures between –11°C and +3°C, the refrigeration capacity varied between 8.5 kW and 15 kW and the COP between 0.32 and 0.57.

The gas fired unit was modified to operate with heat recovered from the exhaust gases of the microturbine. A number of different designs were investigated: a) using the exhaust gases directly on the generator and b) using a heat transfer fluid to transfer heat from the heat recovery heat exchanger (boiler) of the microturbine to the generator. The design the latter arrangement, which was found to be more effective is shown in Figure 15.

Figure 16 illustrates the performance of the absorption refrigeration system with the heat transfer fluid for a range of glycol delivery temperatures. It can be seen that the COP of the unit varies from around 0.58 to 0.67 as the brine flow temperature is increases from -10.0°C to -2.0°C. If the heat transfer fluid pump power is taken into consideration, the system COP drops by approximately 0.08 over the whole range of brine flow temperatures tested.

Comparing the performance of the modified unit (Figure 16) with that of the gas fired unit (Figure 14), it can be seen that the modified unit performs as well if not better than the gas fired unit. At brine flow temperature of -8.0 °C both units have a refrigeration capacity of 12 kW. If the heat transfer fluid pump power is taken into consideration, both units will have a COP of around 0.53. The COP of the modified unit can be increased further if the heat transfer circuit is optimised to reduce pump power.

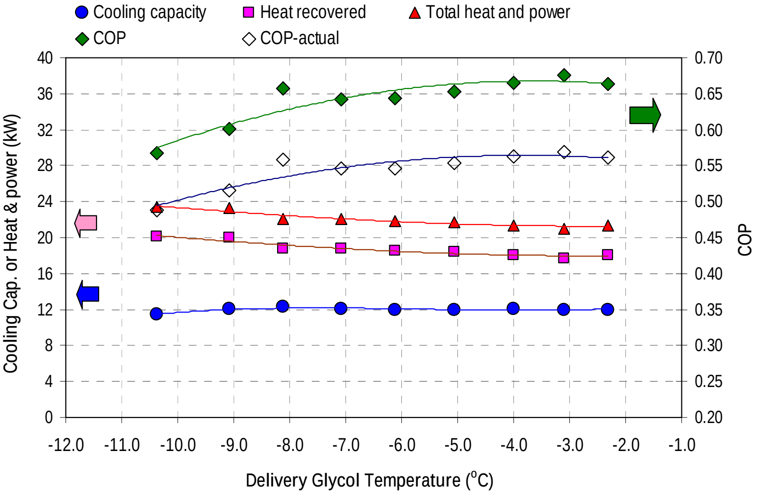


Figure 16: Performance of absorption refrigeration unit driven by heat transfer fluid.

3.1.3 Refrigeration load module

The refrigeration load on the trigeneration system is provided by a combination of secondary refrigerant (propylene glycol) chilled food display cabinet in an environmental test chamber and a dry cooler to balance the refrigeration capacity to the load. The vertical multi-deck display cabinet, shown in Figure 17, was adapted from a direct expansion cabinet.

The direct expansion evaporator coil was replaced by a secondary coil (Figure 18) and the flows and air curtain optimised using CFD to achieve product temperatures below 5.0^{o}C in all positions in the cabinet at climate class III (ISO, 2005) conditions (25^{o}C ambient temperature and 65% RH).

Figure 17: Secondary coil chilled food display cabinet.

Figure 19 shows the product temperature performance of the cabinet on the base shelf (deck) which experienced the highest product temperature close to the return air grille. All product temperatures could be maintained below 5.0^{o}C with brine flow temperature of -7.0^{o}C and return temperature of – 2.0^{o}C.

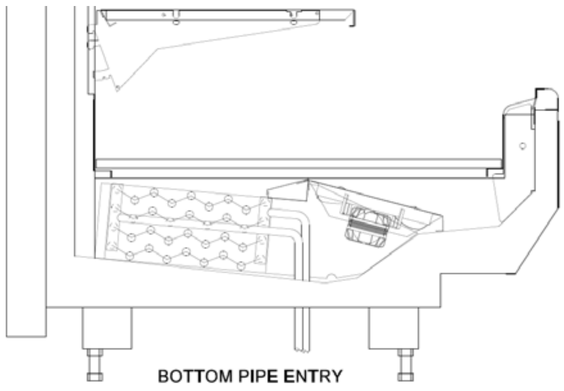


Figure 18: Secondary cooling coil at the base of the cabinet.

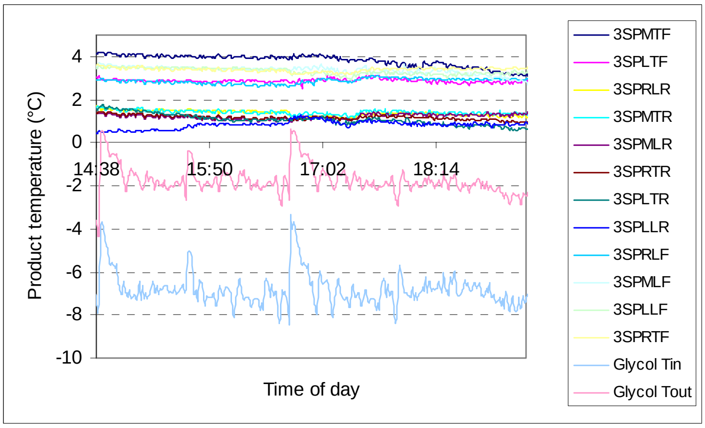


Figure 19: Performance of cabinet with secondary coil.

4. Assessment of the Economic and Environmental Performance of Trigeneration

A number of tools are available in the open literature for the evaluation of the economic and environmental performance of CHP installations. One such tool is the RETScreen spreadsheet model (RETScreen, 2007). This model has been adapted and extended by the authors to enable the evaluation of trigeneration systems.

The developed model can be used to identify the main factors affecting the overall energy efficiency, economic viability and environmental impact for three different operating strategies: full electrical load continuous operation, heat load-following and electrical load-following.

4.1.1 Assessment of microturbine based trigeneration system in a supermarket

To assess the energy and environmental performance of a MGT based trigeneration system in a supermarket compared to a conventional system, a 2800 m^2 sales area supermarket was selected. The variation of the monthly electrical demand of the supermarket is shown in Figure 20.

The average yearly electrical demand is around 395 kWe. Approximately 158 kW$_e$ is used to drive the food refrigeration systems (59 kW$_e$ to power the low temperature refrigeration systems and 99 kW$_e$ to power the medium temperature systems, which on average represents 40 % of

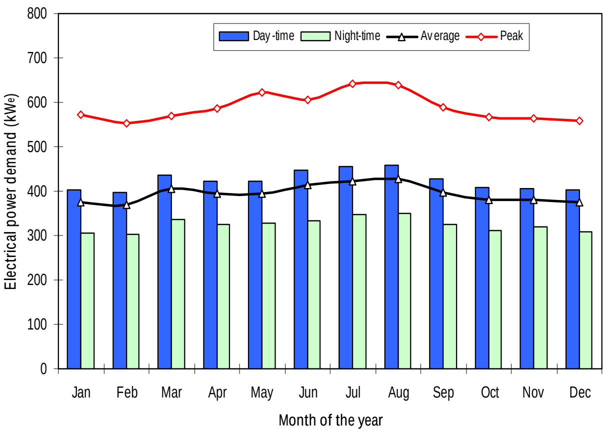


Figure 20: Monthly profile of electrical demand.

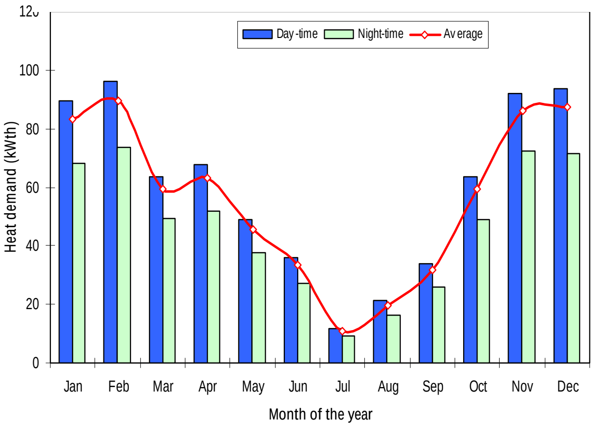


Figure 21: Heat demand profile.

the total electrical demand of the supermarket. The rest 237 kW_e is used for lighting, the HVAC system, the bakery and various other equipment.

It can be seen from Figure 20 that the electrical energy demand of the supermarket increases slightly in the summer months due to the higher ambient temperatures. The increase in the ambient temperature increases the load on the refrigeration plant due to the higher condensing temperature. It also causes an increase in the frosting and defrosting losses of the display fixtures in the supermarket.

The thermal load of the supermarket, Figure 21, is high in the winter months but drops significantly in the summer months due to the increase in the ambient temperature and the reduced need for space heating of the supermarket.

4.2.1 Analysis of Results and Discussion

Figure 22 shows the energy flow diagram for a conventional and a microturbine based trigeneration system in a supermarket. The absorption chiller will be used to partially satisfy the medium temperature refrigeration requirements of the supermarket. The base data assumed for the two systems are given in Table 3.

The results of the economic analysis are shown in Table 4. It can be seen that, for the data used, the tri-generation plant will produce annual savings of the order of £89374 giving a payback period of 4.51 years.

Table 5 shows a comparison between the CO_2 emissions of the conventional and the tri-generation plant. It can be seen that using the

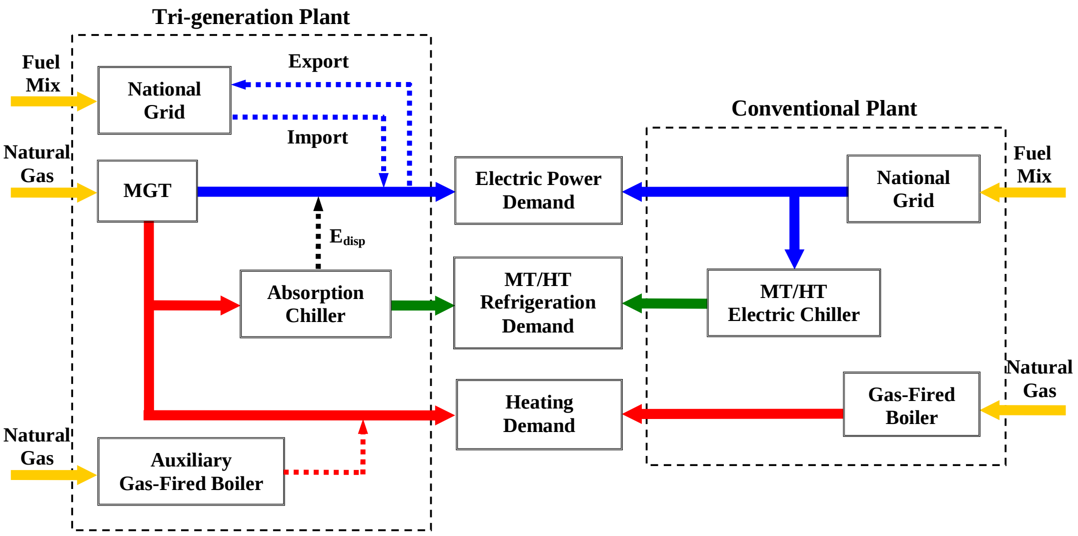


Figure 22: Energy flow diagram for conventional and trigeneration system.

emissions factors for electricity generation and natural gas for the UK, the tri-generation system will result in emission savings of the order of 49 t/CO_2 per year.

The economics and environmental impacts of trigeneration systems are a function of many factors, the most important being the relative cost of electricity and gas, the capital cost of the plant, the efficiency of microturbine or alternative power systems, and the COP of the absorption plant.

Table 3: Base data for system comparison

Fuel price including CCL and VAT	
Electricity bought from grid	0.0841 £/kWh
Electricity sold to grid	0.0740 £/kWh
Gas	0.0253 £/kWh
Standing charge	89 £/month
Availability charge	0.92 £/kWe-month
Power unit	
Generating capacity	80 kWe
Electrical efficiency	29%
Thermal efficiency	70.3 %
Installed cost	982 £/kWe
Owning and Operating costs	0.005 £/kWh
Boilers	
Thermal efficiency	75%
Gross calorific value of natural gas	39.09 MJ/m^3
Net calorific value of natural gas	35.57 MJ/m^3
Absorption units	
Cooling capacity per unit	11 kW
COP	0.5
Installed cost	569 £/kW
Owning and Operating costs	40 £/kW –year
Electric chillers	
COP	2.5
Installed cost	160 £/kW
Owning and Operating costs	70 £/kW –year

Table 4: Results of economic analysis

Conventional plant	
Annual electricity cost	£288464
Annual natural gas cost	£16875
Annual standing charge	£1254
Annual availability charge	£12972
Annual O&M costs for chillers	£21583
Total	£341148
Tri-generation plant	
Net annual electricity cost purchased from grid	£44237
Annual natural gas cost	£187216
Annual standing charge	£1254
Annual availability charge	£3113
Annual O&M costs of tri-generation plant	£24754
Annual electricity sold back to grid	-£8801
Total	£251773
Annual Savings	£89375
Investment	£403081
Payback period	4.51 years

Table 5: CO_2 Emissions

CO_2 Emission factors [18]	
Grid electricity (including transmission and distribution losses)	0.00043 t/kWh
Natural gas	0.00019 t/kWh
CO_2 Emissions from conventional plant	1601 tCO_2/year
CO_2 Emissions from tri-generation plant	1522 tCO_2/year
CO_2 Emissions savings	48.9 tCO_2/year

Following is a sensitivity analysis of the impact of some of these factors.

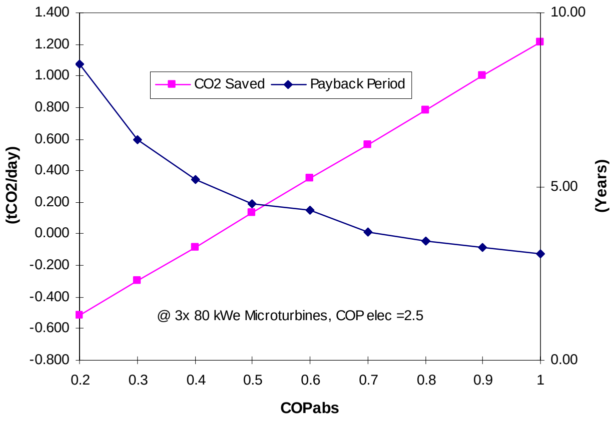


Figure 23: Variation of payback period and emissions savings with COP.

Figure 23 shows the variation of the payback period and CO_2 emission savings with the COP of the absorption refrigeration system. It can be seen that as the COP of the absorption plant increases from 0.5 to 1.0 the payback period reduces from 4.5 to 3.0 years and the CO_2 emission savings increase sevenfold from 0.2 to 1.4 tCO_2 per day.

Figure 24 shows the variation of the payback period with the price of natural gas and a fixed electricity price.

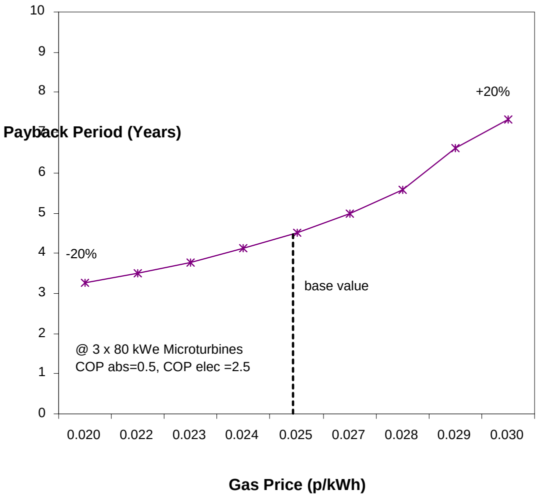


Figure 24: Variation of payback period with gas price.

It is evident that with a fixed electricity price, the payback period is very sensitive to gas prices. With a variation in gas price from -20% to +20% from the base value the payback period varies from 3.3 to 7.3 years which is more than 130%.

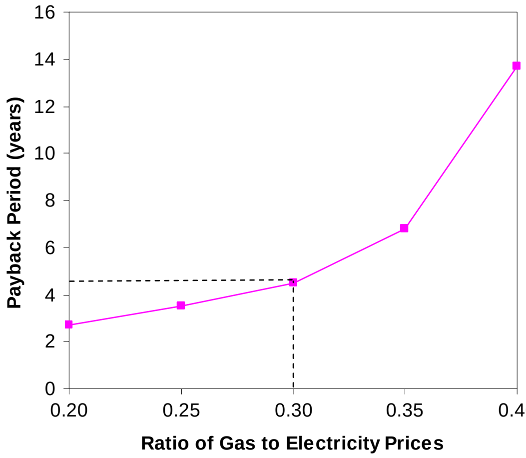


Figure 25: Influence of ratio of gas to electricity prices on payback period.

Figure 25 shows the influence of the ratio of gas to electricity prices on the payback period. It can be seen that for a ratio of 0.2, the payback period is 2.7 years, rising to 4.5 years at a ratio of 0.3. For ratios above 0.3, the payback period increases sharply, rising to 13.7 years at a ratio of 0.4.

It can therefore be concluded that for the assessment of possible tri-generation installations factors such as future trends in the variation of electricity and gas prices should be carefully considered in the feasibility analysis.

5. Conclusions

- Trigeneration is a very efficient way of generating simultaneously electrical power, heating and refrigeration. It can produce substantial energy and greenhouse gas emission savings over separate production of electricity, heat and refrigeration.
- A number of different fuels, such as biofuels, and reliable technologies can be used in trigeneration applications.
- The initial investment costs in trigeneration systems can be relatively high, but payback periods of between 3 and 5 years can be achieved under certain operating conditions.

- The payback period of trigeneration installations is a strong function of the difference between the fuel price and the purchase price for electricity. A ratio of gas to electricity prices of less than 0.3 is required to obtain reasonable payback periods.

- For trigeneration systems to find increased application in the food industry their cost should be reduced. This can be achieved through the development of off the shelf (packaged) systems to simplify integration and reduce installation cost.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the Food Technology Unit of DEFRA for their financial support for this project and the contribution of the industrial collaborators, Bond Retail Services Ltd, Apex Air Conditioning and Bowman Power.

REFERENCES

1. **AEA (2007).** Resource use efficiency in food chains Priorities for water, energy and waste opportunities, Project reference, EAT/ENV/R/2457 (ED05226), 108 pgs.
2. **Bassols, J., Kuckelkorn, B., Langreck, J., Schneider, R., Veelken, H. (2002).** Trigeneration in the food industry, Applied Thermal Engineering**,** Volume 22, Issue 6, Pages 595-602.
3. **Defra (2007).** Report of the food industry sustainability champions'group on waste, http://www.defra.gov.uk/farm/policy/sustain/fiss/pdf/report-waste-may2007.pdf
4. **DTI (2007).** Meeting the Energy Challenge, A White Paper on Energy, 343 pgs. http://www.berr.gov.uk/
5. **DUKES (2006).** Energy statistics: combined heat and power, http://www.berr.gov.uk/energy/statistics/source/chp/page18528.html
6. **FDF (2006).** Food and Drink Federation, Defra Public Consultation on Draft Food Industry Sustainability Strategy, Overall Comments, 6 pgs.
7. **Fuel cell Today (2007),** http:// www.fuelcelltoday.com/media/pdf/
8. **HM Government (2007).** Draft Climate Change Bill, http://www.official-documents.gov.uk/ document /cm70/
9. **HIJC INC (2006) USA,** http://www.adsorptionchiller.bigstep.com/
10. **ISO (2005).** International Standards Organisation, ISO 23953-2, Refrigerated Display Cabinets – classification requirements and test conditions, 86 pgs.
11. **Maidment, G. G., Zhao, X., S. B. Riffa S. B., Prosser, G. (1999).** Application of combined heat-and-power and absorption cooling in a supermarket, Applied Energy Volume 63, Issue 3, July 1999, Pages 169-190.
12. **Maidment, G. G., Prosser, G. (2000).** The use of CHP and absorption cooling in cold storage, Applied Thermal Engineering**,** Volume 20, Issue 12, 1 August 2000, Pages 1059-1073.
13. **Stirling Danmark (2007)** http://www.stirling.dk/
14. **Sugiartha, N., Chaer, I., Tassou, S. A., Marriott, D. (2006)** Assessment of a Micro-Gas Turbine based Tri-generation System in a Supermarket, Proceedings of the International Conference on Fluid and Thermal Energy Conversion, 2006 (FTEC 2006), Jakarta, Indonesia, December 10-16, 2006, ISSN 0854-9346.
15. **Tassou, S. A., I Chaer, I., Sugiartha, N., Ge, Y-T., Marriott, D (2007)** Application of tri-generation systems to the food retail industry, *Energy Conversion and Management*, *Volume 48, Issue 11*, *Pages 2988-2995*
16. **OPET (2004)** Micro and small scale CHP from Biomass, http://akseli.tekes.fi/
17. **OPTIPOLYGEN (2007).** Optimum Integration of Polygeneration systems, http://www.optipolygen.org/
18. **RETScreen (2007).** http://ww.retscreen.net/
19. **Robur (2007).** http://www.robur.it/