Applied Thermal Engineering 29 (2009) 2624–2632

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Trigeneration in food retail: An energetic, economic and environmental evaluation for a supermarket application

N. Sugiartha [a], S.A. Tassou [a,*], I. Chaer [b], D. Marriott [c]

[a] School of Engineering and Design, Brunel University, Uxbridge, Middlesex UB8 3PH, UK
[b] Department of Engineering Systems, London South Bank University, 103 Borough Road, SE1 0AA, UK
[c] New Forest Farm, New Forest Lane, Chilham Kent, CT48BG, UK

ARTICLE INFO

Article history:
Received 16 April 2008
Accepted 15 November 2008
Available online 6 December 2008

Keywords:
CHP
Trigeneration
Food retail
Micro-gas turbine
Absorption chiller
Operating strategy
Supermarket

ABSTRACT

This paper presents results on the evaluation of energy utilisation efficiency and economic and environmental performance of a micro-gas turbine (MGT) based trigeneration system for supermarket applications. A spreadsheet energy model has been developed for the analysis of trigeneration systems and a 2800 m^2 sales area supermarket was selected for the feasibility study. Historical energy demand data were used for the analysis, which considered factors such as the fraction of the heat output used to drive the absorption chillers, the chiller COP and the difference between electricity and gas prices. The results showed that energy and environmental benefits can be obtained from the application of trigeneration systems to supermarkets compared to conventional systems. The payback period of natural gas driven trigeneration systems and greenhouse gas emissions savings will depend on the relative gas and electricity prices and the COP of the vapour compression and absorption systems. It was also shown that operation at full electrical output gives a better performance than a heat load-following strategy due to the reduction of the electrical generation efficiency of the MGT unit at part load conditions.

1. Introduction

In the UK, over 40% of the average electrical load in large supermarkets is used to drive the refrigeration systems [1]. Vapour compression chillers are normally used to produce the cooling required by the refrigerated display cabinets, cold rooms and air conditioning system. At the same time, supermarkets have a requirement for hot water and space heating in the winter in order to maintain comfort conditions. This heating load is normally covered by gas-fired boilers. The heat demand for space heating varies seasonally and this determines the heat load pattern of the supermarket. Demand for hot water is quite low and remains fairly constant throughout the year. The highest heating load normally occurs during the winter months. In the summer months, heat demand is fairly low.

A combined heat and power (CHP) or cogeneration system is a potential method to reduce energy consumption and to improve energy system efficiency [2–6]. The simultaneous heat and electrical power generation from the CHP plant require a coincident site demand for the heat and electrical power in order to achieve economic operation. In supermarket applications, the low heat demand in the summer months makes it difficult to achieve high CHP plant utilisation. High and constant utilisation can be achieved if some of the heat available from the plant is used to drive sorption refrigeration systems. This concept is known as combined heat, refrigeration and power (CHRP), or CHCP (combined heat cold and power). In this paper, we will refer to trigeneration which is the more modern definition of the concept.

Some examples of the application of trigeneration systems in the food industry have been presented by Bassols et al. [7] and Colonna and Gabrielli [8]. These involved ammonia–water absorption systems driven by gas engines and gas turbines.

In recent years, significant attention has been placed on the assessment of trigeneration systems and their ability to improve energy utilisation efficiency, reduce greenhouse gas emissions and produce economic savings. A number of evaluation models have been developed for feasibility studies.

Heteu and Bolle [9] presented an energy model for the comparison between trigeneration systems and separate heat and power production in terms of quality indices for primary energy and carbon emission savings. The model assumes full utilisation of electricity and heat and was used to carry out sensitivity analyses of primary energy consumption for different quantities of heat used to drive an absorption chiller.

Maidment et al. [10] developed a model to evaluate primary energy and economic savings for a conventional CHP gas engine-based system and a CHP system coupled to a single-stage ammonia–water absorption chiller for a typical 2000 m^2 total floor area supermarket. The authors used the BIN method to determine electricity and heat consumption. The results showed that the trigeneration system could offer better performance than a con-

* Corresponding author. Tel.: +44 1895266938; fax: +44 1895256392.
E-mail address: Savvas.Tassou@brunel.ac.uk (S.A. Tassou).

1359-4311/$ - see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.applthermaleng.2008.11.018

Nomenclature

CC	cooling capacity
CCL	climate change levy
CHP	combined heat and power
CIT	compressor inlet temperature
COP	coefficient of performance
E	electrical power
EC	energy costs
EM	CO_2 emissions
EMF	CO_2 emission factors
ES	energy supply
F	fuel consumption
FESR	fuel energy saving ratio
FLC	full load continuously
GCV	gross calorific value
HLF	heat load-following
H/*P*	heat to power ratio
HT	high temperature
LT	low temperature
MGT	micro-gas turbine
NCV	net calorific value
PB	payback period
Q	heat energy
T&D	transmission and distribution
UC	unit cost
VAT	value added tax

Greek symbols

α	fraction of micro-gas turbine heat output diverted to drive absorption chillers
η	efficiency

Subscript

abs	absorption system
aux, boiler	auxiliary boiler
c	cooling
conv	conventional system
conv,grid	grid electricity of the conventional plant
disp	displaced
e	electrical
el	electric-driven vapour compression chiller
exh	exhaust gas
f	fuel
grid	National grid
NG	natural gas
ov,tri	overall trigeneration system
ref	reference
th	thermal
tri	trigeneration plant

ventional CHP system in terms of both payback and primary energy savings.

RETScreen [11] offers a spreadsheet model that enables the evaluation of CHP systems and allows the use of various combinations of power, heating and cooling plant. The model can be used to carry out performance and economic analyses and determine greenhouse gas emissions for separate energy production systems and combined heat and power generation. The model also allows the investigation of different operating strategies such as full power, power-following and heat-following modes but part load efficiency of prime movers is not considered.

Kong et al. [12] introduced a model to determine optimal strategies to minimise the overall cost of energy for trigeneration systems using a simple linear programming method. They characterised the optimal operation of the trigeneration system by considering fixed load sets in the form of ratios of cooling load to turbine electrical generation capacity. Variation of the cooling load while keeping heating and electrical loads fixed was used as a parametric variable to determine optimum values of turbine load factor and exhaust heat fraction allocated for cooling.

Cardona and Piacentino [13] developed a methodology for sizing trigeneration systems in the hotel sector based on thermal and cooling consumption data. The size of the prime mover was based on the variation of heating and cooling demand throughout the year and the sum of the energy requirement to satisfy the maximum coincident heating and cooling demand.

Although trigeneration systems have been applied to the food manufacturing sector, interest in their application to the food retail sector is only recent. This has mainly been due to the unavailability of commercial size low temperature and low cost absorption refrigeration systems off-the-shelf. A number of recent applications in the retail food industry in the UK have been for space heating and cooling but retail food chains and equipment suppliers are now considering systems for refrigeration applications. Ongoing research at Brunel University is aimed at accelerating this process through the development of assessment tools and the design of systems for retail food refrigeration applications [14].

This paper describes a methodology for the evaluation of the energy utilisation efficiency, economics and environmental performance of a trigeneration system in a supermarket. The model utilises monthly energy demand data for a 2800 m^2 sales area supermarket and assumes a micro-gas turbine based trigeneration system able to provide refrigeration down to −12 °C. Test results on the performance of the micro-gas turbine and absorption refrigeration system obtained in the laboratory were used as inputs to the model. Two different control strategies were considered: full load-continuous operation and heat load-following operation.

2. Energy demand of case study supermarket

The supermarket considered in the study is located in the South of England and has a sales area of 2800 m^2. The energy flows in the supermarket are illustrated in Fig. 1. The average electrical demand of the store is 395 kW_e with approximately 158 kW_e required for food refrigeration, of which 59 kW_e is for the low temperature frozen food display cabinets and cold rooms and 99 kW_e for the high temperature chilled cabinets and cold rooms. This represents 40% of the total electrical demand of the whole supermarket. The rest of the electrical demand, 237 kW_e, is related to lighting, ventilation and air conditioning, bakery and various other auxiliary equipment. The average heat demand is 55 kW_{th}.

The monthly variation of electrical and heat demand is shown in Fig. 2. As can be seen from Fig. 2(a), the average monthly electrical demand is fairly constant throughout the year, increasing slightly in the summer months due to the higher outdoor air temperature. Daytime demand (7:00–24:00 h) is higher than nighttime demand primarily due to lower shopping activity and lower nighttime temperatures that lead to lower condensing temperatures and refrigeration system power consumption. Other loads that contribute to the higher daytime demand are air conditioning in the summer months that operates during opening hours and lighting. The monthly variation of daytime and nighttime heat demand is shown in Fig. 2(b). It can be seen that the variation of heat