Alexandria Engineering Journal (2013) **52**, 151–158

FACULTY OF ENGINEERING
ALEXANDRIA UNIVERSITY

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Alexandria Engineering Journal

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REVIEW

Economical analysis of combined fuel cell generators and absorption chillers

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Received 15 August 2011; revised 16 December 2012; accepted 26 December 2012
Available online 1 February 2013

KEYWORDS

Economical aspects;
Co-generation system;
Fuel cell;
Absorption system

Abstract This paper presents a co-generation system based on combined heat and power for commercial units. For installation of a co-generation system, certain estimates for this site should be performed through making assessments of electrical loads, domestic water, and thermal demand. This includes domestic hot water, selection of the type of power generator, fuel cell, and the type of air conditioning system, and absorption chillers. As a matter of fact, the co-generation system has demonstrated good results for both major aspects, economic and environmental. From the environmental point of view, this can be considered as an ideal solution for problems concerned with the usage of Chlorofluoro carbons. On the other hand, from the economic point of view, the cost analysis has revealed that the proposed system saves 4% of total cost through using the co-generation system.

Contents

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Peer review under responsibility of Faculty of Engineering, Alexandria University.

ELSEVIER Production and hosting by Elsevier

http://dx.doi.org/10.1016/j.aej.2012.12.004

Nomenclature

Abbreviations

AAC	average annual cost
AOC	annual operating cost
CFC	chlorofluorocarbon
Cg	co-generation
CHP	combined heat and power
EPA	environmental protection agency
FC	fuel cell
HCFC	hydro chlorofluorocarbon
Hex	heat exchanger
HFC	hydro fluorocarbon
HG	high grade
HRC	heat rejection cost
i	annual interest rate
I	initial cost
kW	kilo watt
L.F	load factor
LG	low grade
MCFC	molten carbonate fuel cell
NGS	natural gas system
P_c	present cost
PAFC	phosphoric acid fuel cell
PEMFC	proton exchange membrane fuel cell
PNHR	plant net heat rate
SOFC	solid oxide fuel cell
TAC	total annual cost
U$	USA dollar
VAS	vapor absorption system
VCS	vapor compression system

Subscripts

C	initial cost
CO_2	carbon dioxide
I	irreversibility
j	at month j of the year
K	at hour k of the day

Superscripts

j	at month j of the year
K	at hour k of the day
m	monthly
n	number of days per month

1. Introduction

Co-generation is the simultaneous production of electricity and thermal energy from the same fuel source. In fact, it can be applied to any commercial, industrial, or institutional facility where there is a simultaneous need for both heat energy and electrical power. Actually, it offers several advantages over central electricity generating stations:

1. Fuel use efficiency is much higher, often twice as high, since the rejected heat is normally utilized in a useful process or hot water heating.
2. Because of its higher efficiency, co-generation is also economically and financially more attractive than central power generating stations.
3. Much, if not most, of the cogenerated electricity is consumed at the generation site, thus saving transmission line capacity and costs.
4. Unlike central power generating stations, co-generation can be cost-effective even in very small capacities (as low as 50–100 kW).
5. Most co-generation projects have a much shorter lead time than the large central generating stations, as shown in Fig. 1 [1].

1.1. Fuel cell description

Fuel cells are the electrochemical devices which convert the chemical energy of a reaction directly into electrical energy. The basic physical structure or building block of a fuel cell consists of an electrolyte layer in contact with a porous anode and cathode on either side.

A schematic representation of a fuel cell with the reactant/product gases and the ion conduction flow directions through the cell is illustrated in Fig. 2 [1].

Fuel cells are named or defined according to their electrolyte, i.e., phosphoric acid, molten carbonate, solid oxide, or proton exchange membrane. During the last 50 years, a number of diverse types of fuel cells have been developed. At present, the most dominant type is the Proton Exchange Membrane Fuel Cell (PEMFC). In fact, the PEMFCs are the most versatile of all fuel cells and, depending on their size (ranging from less than 1 W to 300 kW), they can propel anything from small electronic devices to buses and submarines.

However, other fuel cells, though they have their own advantages, are less flexible. For example, Molten Carbonate Fuel Cells (MCFCs) are only used in stationary applications (250 kW and above), like Phosphoric Acid Fuel Cells (PAFCs)

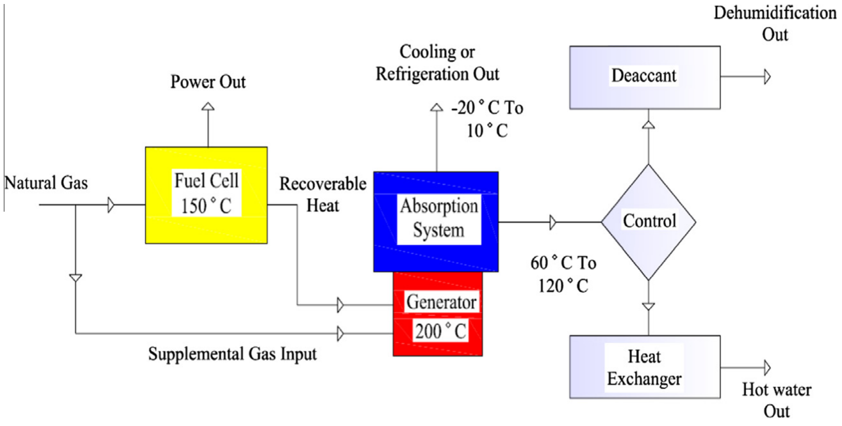

Figure 1 Cogeneration station.

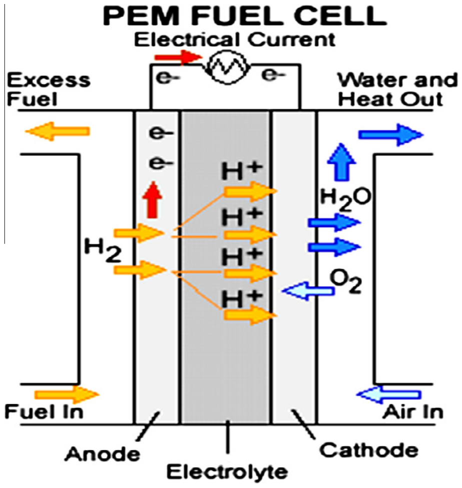

Figure 2 Schematic of an individual fuel cell.

(50 kW and above). Moreover, Direct Methanol Fuel Cells (DMFCs) are best suited for the applications where less than 1 kW is required. Furthermore, Solid Oxide Fuel Cells (SOFCs) are more flexible (1 kW to several 100 kW), but they are not, as the technology now stands, suitable for use in vehicles.

2. The concept of co-generation

In a central-station steam thermal plant, fuel is burned to produce high-temperature and high pressure steam, which are then passed through a turbine to generate electricity. However, even in the most efficient of these plants, less than 40% of the available energy (heat) contained in the fuel is converted into electricity while the remainder is lost in the atmosphere. Some of the energy loss is accounted for by combustion gases that escape to the atmosphere through the boiler stack. Nevertheless, most of the energy is wasted in the condensation and cooling of steam and water after they have passed through the turbine.

Fig. 3 illustrates the basic idea of co-generation; yet, a large number of variations on this matter are possible. All of them combine the generation of a mechanical or electrical power through the utilization of waste heat. Generally speaking, the term co-generation is widely used and universally accepted to describe both the concept of the combined production of power and heat as well as the equipment or systems utilized to produce power and heat in this way. Another form commonly applied to such systems and equipment, especially in Europe, combines both heat and power, often referred to in the literature as CHP [2–4].

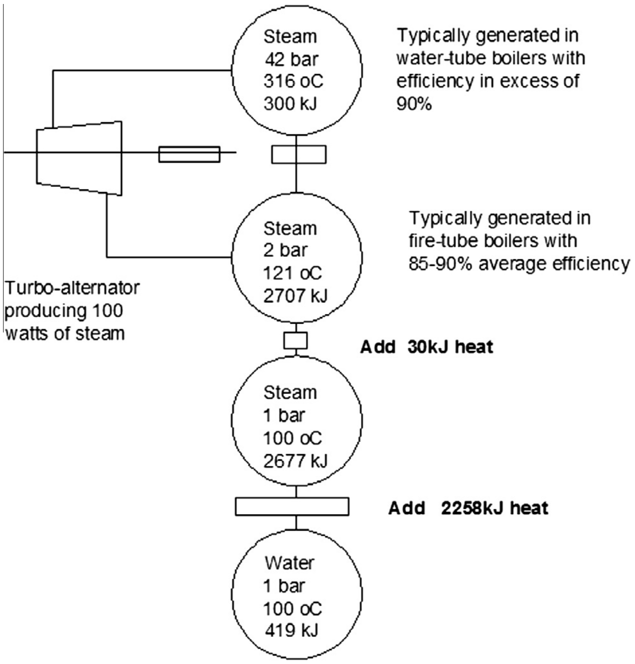

Figure 3 The energy requirement for cogeneration.

3. Natural gas as a heat source for fuel cell and absorption chillers

The availability of a new generation of more efficient and reliable gas cooling products from a number of manufacturers is only one reason for the renewed interest in gas cooling. Other recent developments which contribute to the momentum toward natural gas cooling include the following:

- The natural gas clean environmental effect through CFC free technology.

Table 1 Electric daily load demand.

Daily load (W h/day)	Peak load (We)	Min load (We)	*n* (units)	Peak load/*n* (We)
22,445,252	1969799.038	644166.688	2	984899.519

Table 2 Site capacity degradation.

Degradation	%
Temp. capacity degradation	0
Altitude capacity degradation	0
De-rating until overhaul (fuel processor and stack change)	16
Auxiliaries consumption	4.2
Combined degradation factor	1.24047619
Actual rating for unit (watt)	1,222,000

- The desire to cut energy costs and eliminate peak electric demand charges.
- The financial incentives from the gas industry.
- The need for improved indoor air quality.
- The low natural gas prices [5,6].

Standalone combined heat and power is based on electrical load which consist of two fuel cell generators and absorption chiller, while natural gas is used as a heat source for fuel cell and absorption system [7].

In this case, selection of fuel cells is based on electrical load demand by taking into consideration the maximum load and minimum load according to the chronological load curve for the case study. For example, if we select 1FC for maximum load and minimum load less than 10–15%, this FC will not work as shown in Tables 1 and 2. Thus, optimization of the selection of fuel cell number should be performed in order to meet this load. Therefore, the following Figs. 4–6 illustrate the selection of size on the seasons. Moreover, there is the site capacity degradation which affects the performance of a generator [2,8].

A theoretical analysis was completed of the electrical load in summer for two different systems: the peak load of a fuel cell and the peak load for two fuel cells relative to time, as shown in Fig. 4.

A theoretical analysis was conducted of the electrical load in winter for two different systems: the peak load of one fuel cell and the peak load of two fuel cells relative to time, as illustrated in Fig. 5.

A theoretical analysis was done of the electrical load in Autumn and Spring for two different systems: the peak load of one fuel cell and the peak load of two fuel cells relative to time, as demonstrated in Fig. 6.

4. Absorption cooling systems

It has been on the market for over 100 years. In the late 1800s, absorption chillers were used for large refrigeration plants. However, during the 1950s, technological advances occurred, and the systems were fine-tuned for commercial use. Conversely, their popularity declined in the late 1970s due to the inexpensive cost and abundance of electricity [9,10].

Similar to the vapor compression-cycle, absorption chillers rely on a cycle of condensation and evaporation to produce cooling. Both systems have an evaporator and coil condenser which expands the refrigerant from high to low pressure between the condenser and evaporator. The mechanical compressor of the vapor-compression cycle of condensation and evaporation is replaced by a heat source in the absorption chiller. This heat source is either directly fired using a burner or indirectly fired using steam, hot water, or waste heat from other processes. Most absorption systems use a water and lithium bromide combination as working fluid [11,12].

Absorption chillers are available in two types. The first, a single-effect, is operated with low-grade waste heat. On the other hand, the second, the double-effect, requires either direct firing or high-grade steam as the heat source [9,13].

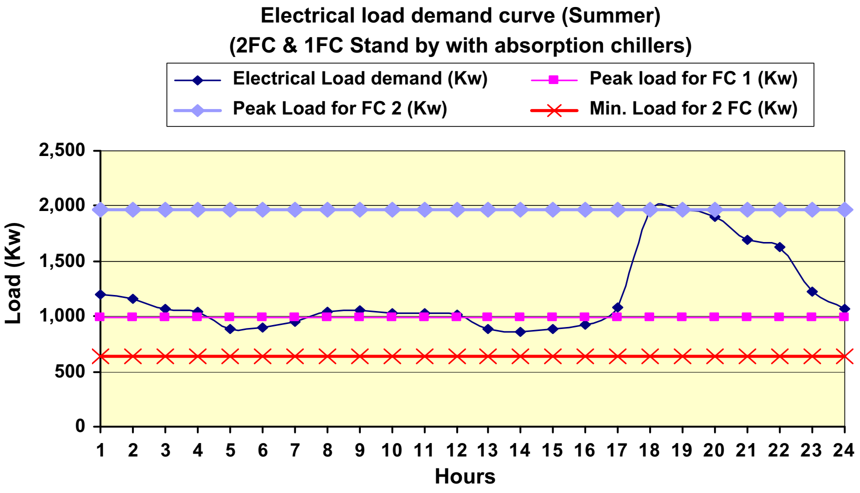

Figure 4 Electric load demand curve in summer relative to time.

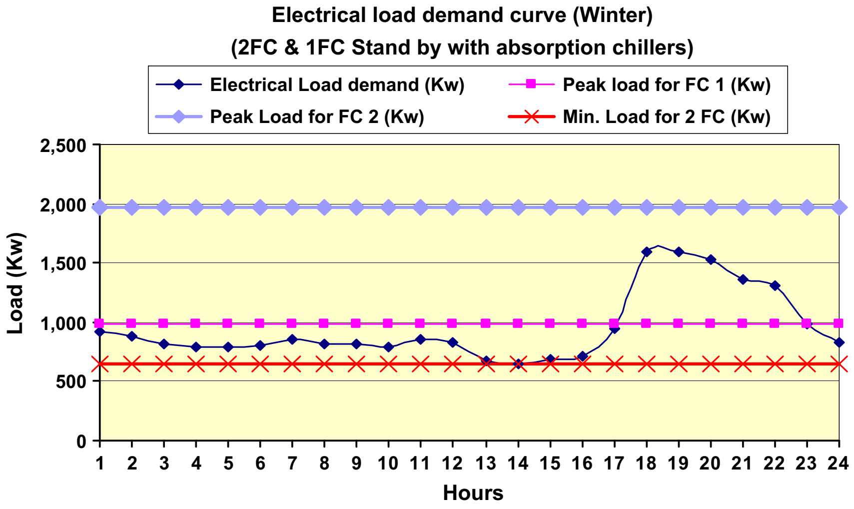

Figure 5 Electric load demand curve in winter relative to time.

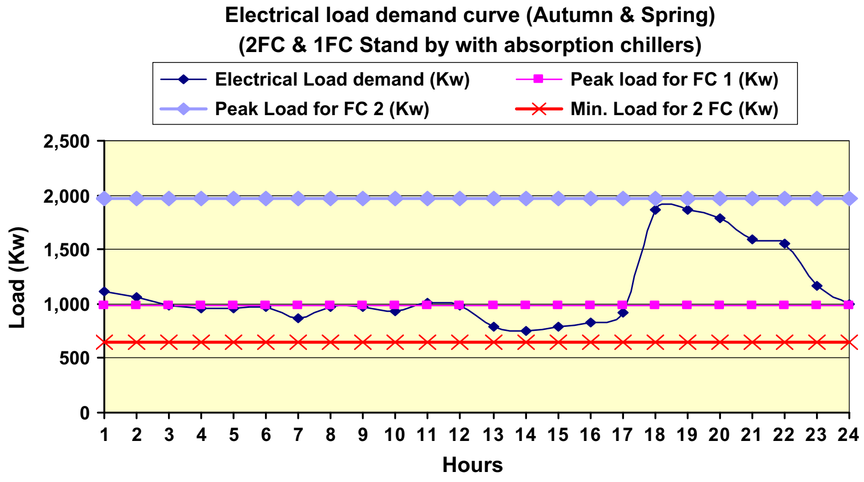

Figure 6 Electric load demand curve in Autumn and Spring relative to time.

5. Cost analysis

An initial estimate of the costs must be computed in order to determine the economic feasibility of any project.

Therefore, there is a method to compare the cost of any two or more systems. That is the Life-Cycle Cost (LCC), which includes all cost factors (first cost, operating cost, maintenance, replacement and estimated energy use) and can be used to evaluate the total cost of the system over the complete life of the system.

Thus, the data of the required costs presented in this study produce a very good estimate of the capital costs and operating costs. Eq. (1) confirms that the total cost of any system consists of three main variables, namely the initial cost, the operating cost, and finally the maintenance cost.

$$\text{Total cost} = f(\text{initial cost} + \text{operating cost} + \text{maintenance cost})$$

$$\text{Total cost} = \sum_{k=1}^{k} I_k + \sum_{j=1}^{12} (I + i_m)^{(12-j)} * \sum_{k=1}^{k} O^m_{j,k} + \sum_{k=1}^{k} M_k \qquad (1)$$

The following section presents details of how these various costs are evaluated [7,14,15].

5.1. Initial costs

The initial costs for the single-effect vapor absorption systems comprise the absorption machine, heat rejection equipment, and natural gas system.

The initial cost of the vapor compression system includes the vapor compression chiller and the heat rejecting equipment. The physical size of the absorption system is larger than the size of the vapor compression system. Consequently, this increase in size requires a larger building, moving equipment, and support systems. Consequently, this results in a higher installation cost for the vapor absorption system.

Furthermore, the electric supply for a vapor compression system needs to be upgraded by either increasing the electrical capacity of the electric substation or building a new substation.

The initial cost, therefore, should include, in addition to the purchase and installation expenses of the systems, the various subsystems necessary for an effective operation. This

Table 3 Initial cost of the two systems.

Initial cost		
	Single-effect VAS	Vapor comp. system
Absorption chillers and VC system		
Machine capacity (kW)	200 kW	
Total cost ($)	59,000	43,500
Life time (year)	20	10
Heat rejection equipment		
Total cost ($)	26,000	17,250
Life time (year)	20	20
Natural gas system		
Cost ($)	15,000	0
Life time (year)	20	0

comprises piping, wiring, and specific structures. Table 3 shows the initial cost of both systems.

In addition, the heat rejection equipment for the application considered in this work is a cooling tower. The cooling towers for both vapor absorption systems (single and double-effect) have a centrifugal or propeller type fan. Although the centrifugal fan has a higher capital cost, it has been selected for two practical reasons: the lower level of noise, as well as its lower operating costs compared to the propeller fan.

The cooling tower for the vapor absorption system is between one and a half and two times larger than that for a vapor compression system of a similar size.

The costs of the auxiliary equipment cover the electric pump motors, fan motors, and a water treatment system for the cooling tower [8,16]. The cost of natural gas auxiliary is zero because it does not contain a natural gas system.

5.2. Operating costs

Operating costs, which encompass the costs of electricity, wages of employees, supplies, water and materials, are those incurred by the actual operation of the system [8,16]. All new plants may be assumed to be fully automatic. Thus, estimation of labor is very rarely relevant. For the purpose of comparison between the two systems and taking into account the low labor cost in Egypt, the assumption of zero difference in the operating labor cost for the two systems is made. Hence, the electrical operating costs for the vapor absorption systems comprise the heating water pump, condenser water pump, generator water pumps and cooling tower fans:

$$O^{m}_{(vAs)} = n^{*}_{m}\mathrm{EC}^{*}\sum_{k=1}^{k}E_{k} \qquad (2)$$

In regard to the vapor compression system, the operating costs are dominated by the electricity required to drive the compressor. Additional electricity is used to drive the condenser water pump and the cooling tower fans. The annual operating cost can be displayed in Table 4. The monthly electric operating cost of the vapor compression system is proportional to its monthly electric energy consumption [8]:

$$O^{m}_{(vcs)} = n^{*}_{m}\mathrm{EC}^{*}\int_{k=1}^{24}\frac{Q_{k}}{\mathrm{COP}_{k}}\cdot dt \qquad (3)$$

A theoretical analysis was conducted of the different cooling capacities between 200 and 800 kW and the annual initial and operating costs of two different systems, namely, the vapor compression system and vapor absorption system which were calculated as shown in Fig. 7.

Table 4 Annual operating cost.

Operating costs		
Price of kW h ($/kW h)	0.08	
VAS and VCS machines	VAS	VCS
Total use (kW h/year)	34,840	536,930
Annual cost ($)	3026	42,954
Price of kW h ($/kW h)	0.06	–
Natural gas system	VAS	VCS
Total use (kW h/year)	265,536	–
Annual cost ($)	15,932	–
Cooling water pump		
Cooling water pump motor efficiency	0.68	
Total use (kW h/year)	56,290	42,530
Annual cost ($)	5104	3400
Cooling tower fans		
Fans efficiency	0.6	
Fan partial use factor	0.4	
Total use (kW h/year)	50,715	33,810
Annual cost ($)	4060	2705
Total annual operating cost ($)	28,122	49,059

5.3. Maintenance cost

Maintenance cost is the final cost to be estimated for air conditioning systems. There are various levels of maintenance, which may be applied to building HVAC services. The three most common levels are the run-to-failure, the preventive and finally the predictive maintenance.

Maintenance cost is difficult to quantify because it depends on a large number of variables, such as, local labor rates, their experience, the age of the system and operating time.

The maintenance cost for the heat rejection subsystem tends to be higher for the VAS due to more rapid scaling; however, this could be offset by the maintenance cost of the VCS because it is a work-operated cycle.

Maintenance costs cited in various studies reveal that the maintenance costs of a vapor absorption system range from 0.6 to 1.25 times the maintenance costs of the vapor compression system [17].

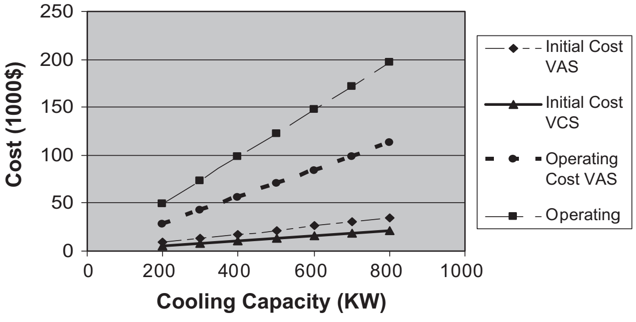

Figure 7 Initial and operating cost for VAS and VCS relative to cooling capacity.

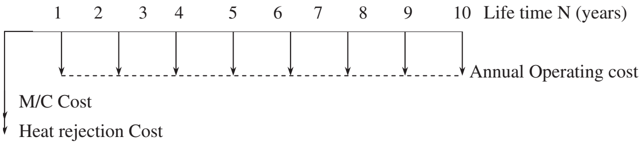

Figure 8 Cash flow diagram for VCS {AAC}.

5.4. Average annual cost comparison

With the average annual cost method, all costs occurring over a period are converted to an equivalent uniform yearly amount. Broadly speaking, the AAC comparison method is deemed as one of the most convenient methods, particularly for the systems composed of several subsystems with unequal life spans. Actually, this method does not require the assumption of replacement of a system. Fig. 8 represents the cash flow diagram for the VCS as there is no more assumption of the system replacement, more realistic in this case.

The AAC for the vapor absorption systems and the vapor compression system is the summation of the AAC values for the system and subsystems and the annual operating cost, Eqs. (4)–(7), respectively.

$$\mathrm{AAC_{VAS}} = \mathrm{AA}_{M\backslash C} + \mathrm{AA_{HRC}} + \mathrm{AA_{NGS}} + \mathrm{AOC} \tag{4}$$

$$\mathrm{AAC_{VCS}} = \mathrm{AA}_{M\backslash C} + \mathrm{AA_{HRC}} + \mathrm{AOC} \tag{5}$$

$$\mathrm{AAC} = P_C(A/P, i\%, N) \tag{6}$$

$$\mathrm{AAC} = P_C\left[\frac{i(1+i)^N}{(1+i)^N - 1}\right] \tag{7}$$

6. Discussion of results

An analysis of the overall initial and operating costs for the two air conditioning systems have been developed in this work. This analysis describes two economic techniques for evaluating the systems. In addition, the work also pays special attention to cash flow over the complete life of the project (Life-Cycle Costing, LCC). The following Table 5 illustrates an equivalent annual cost comparison.

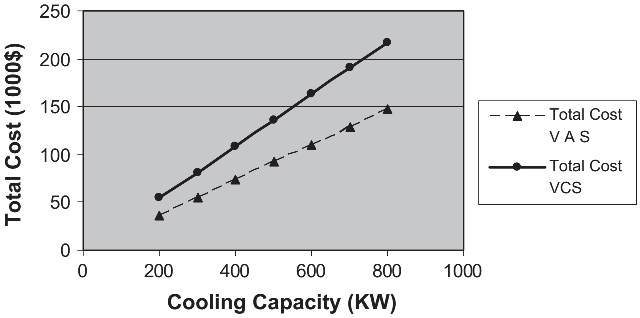

Figure 9 Total cost for VAS and VCS relative to cooling capacity.

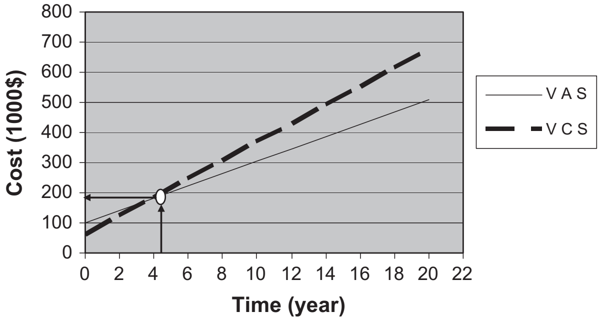

Figure 10 Total cost for VAS and VCS relative to time.

A theoretical analysis was performed of the different cooling capacities between 200 and 800 kW and the total cost of two different systems. These were the vapor compression system and vapor absorption system which were calculated and displayed in Fig. 9.

A theoretical analysis was conducted of the total cost of the two different systems: vapor compression system and vapor absorption system relative to time, as shown in Fig. 10.

The figure reveals that the initial cost of the VAS is higher than that of the VCS system; however, after about 4 years the break-even point occurs and the total cost of the VAS will be recommended to use because it will have a decreasing trend on the long run.

Table 5 The equivalent annual cost comparison results.

Average annual cost comparison (AAC)

	VAS single-effect	VCS
Machine cost	59,000	43,500
Heat rejection cost	26,000	17,250
Natural gas system cost	15,000	0
AAC for machine cost	5100	3792
AAC for heat rejection	2265	1503
AAC for solar heat collection	1307	0
AAC for initial cost (1000 $/year)	8.672	5.295
Annual operating cost AOC (1000 $/year)	28.122	49.059
Annual interest rate	0.06	0.06
Life span (years)	20	10
Total average annual cost (1000 $)	36.794	54.885

7. Conclusion

Provided the co-generation is optimized in the way described above (i.e. sized according to the heat demand), the following benefits will emerge:

1. Increased thermal efficiency of energy conversion and co-generation use.
2. Lower emissions to the environment, in particular of CO_2, the main greenhouse gas.
3. In some cases, where there are biomass fuels and some waste materials, such as refinery gases, process or agricultural waste (either an aerobically digested or gasified), these substances can be used as fuels for co-generation schemes. Thus, they will lead to the increase in the cost-effectiveness and reduction of the need for waste disposal.
4. Large cost savings, providing additional competitiveness for industrial and commercial users, and presenting affordable heat for domestic users.
5. There would be available an opportunity to move towards more decentralized forms of electricity generation, where a plant is designed to meet the needs of local consumers, providing high efficiency, avoiding transmission losses and increasing flexibility in system use. This will particularly be the case if natural gas is the energy carrier.
6. Improved local and general security of supply – local generation, through co-generation, can reduce the risk that consumers may be left without supplies of electricity and/or heating.
7. An opportunity to increase the diversity of generation plant, and provide competition in generation. Co-generation provides one of the most important vehicles for promoting liberalization in energy markets.
8. From the economic point of view, the cost analysis has suggested that the proposed system saves 4% of total cost by using the co-generation system.

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