LIFE CYCLE COST ANALYSIS OF WASTE HEAT OPERATED ABSORPTION COOLING SYSTEMS FOR BUILDING HVAC APPLICATIONS

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ABSTRACT

In this paper, life cycle cost analysis (LCCA) of waste heat operated vapour absorption air conditioning system (VARS) incorporated in a building cogeneration system is presented and discussed. The life cycle cost analysis (LCCA) based on present worth cost (PWC) method, which covers the initial costs, operating costs, maintenance costs, replacement costs and salvage values is the useful tool to merit various cooling and power generation systems for building applications. A life cycle of 23 years was used to calculate the PWC of the system for annual operating hours of 8760 and the same is compared with the electric based vapour compression chiller (VCRS) of same capacity. The life cycle cost (LCC) of waste heat operated absorption chiller is estimated to be US $ 1.5 million which is about 71.5 % low compared to electric powered conventional vapour compression chiller. From the analysis it was found that the initial cost of VARS system was 125 % higher than that of VCRS, while the PWC of operating cost of VARS was 78.2 % lower compared to VCRS. The result shows that the waste heat operated VARS would be preferable from the view point of operating cost and green house gas emission reduction.

1. INTRODUCTION

Industries depending heavily on electrical energy are the most affected ones. Industries are encouraged to have their own captive power stations. Diesel generating sets are the most common captive power stations. The exhaust gases and jacket water of these gensets have a very large amount of heat. Which is wasted, can be effectively exploited.

Nomenclature

COP	Coefficient of performance
d	discount rate
DEVARS	double effect vapour absorption refrigeration system
EC	electricity cost ($)
HFO	heavy fuel oil
HT	high temperature
HRSG	heat recovery steam generator
LCC	Life cycle cost
LCCA	life cycle cost analysis
LT	low temperature
n	operating hours per annum (h)
N	analysis period (years)
O	operating cost ($)
P	present value ($)
PWC	present worth cost ($)
TP	total power input per hour (kWh)
UCPG	unit cost of power generation ($)
VARS	vapour absorption refrigeration system
VCRS	vapour compression refrigeration system
Subscripts	
y	year
cogen	cogeneration
O	operating cost ($)
M	maintenance cost ($)
RE	replacement cost ($)
SV	salvage value ($)
Superscripts	
y	year

Generally a cogeneration system for air-conditioning uses waste heat or exhaust gases in order to feed a vapour absorption refrigeration system (VARS). The main difference between cogeneration system and typical methods of electric generation is the utilization of the waste heat rejected from the prime mover in order to satisfy the thermal demand of the facility (cooling or heating).

This helps reduce problems related to global environment, such as greenhouse effect from CO_2 emission resulting from the combustion of fossil fuels in utility power plants and the use of chlorofluorocarbon refrigerants, which is currently thought to affect depletion of the ozone layer. The ban on fluorocarbon fluids has been an impetus towards research into environmental friendly refrigerants such as water. One way to reduce CO_2 emissions is to utilize low-grade heat sources in heat powered VARS. The primary energy benefit of waste heat operated absorption system is reduction in operating cost by avoiding peak electric demand charges. The end goals of cogeneration systems are to ensure reduction of primary energy, cost, emissions, or a combination of all of them.

The main objective of this paper is to analyze the life cycle cost (LCC) of waste heat operated absorption air conditioning system (VARS) incorporated in a building cogeneration system. The PWC method for LCC was used to evaluate total costs. The unit is powered by an exhaust gas and jacket cooling water from 1.9 MW heavy fuel oil (HFO) fired reciprocating engine cogeneration system. The chiller achieves 375 TR of cooling capacity at the COP of 1.15 by rejecting heat through a cooling tower with a capacity of 2395 kW. A life cycle of 23 years was used to calculate the PWC of the system for annual operating hours of 8760 and the same is compared with the electric based vapour compression chiller (VCRS) of same capacity.

2. DESCRIPTION OF COGENERATION POWERED VARS

The schematic diagram of HFO based building cogeneration system is shown in Figure 1. From this figure it can be seen that HFO is supplied to the power generating unit to produce electricity need for the building. The waste heat from exhaust gases is recovered by using heat recovery steam generator (HRSG) to generate hot water. The hot water and jacket water is used as heat resource of VARS. The VARS driven by waste heat from exhaust gas and jacket water is double effect vapour absorption system (DEVARS). Table 1 shows the operating parameters of VARS

Table 1
Operating parameters of VARS

Operating Parameters	Values
Capacity of the VARS (TR)	375
Chilled Water flow rate (m^3/h)	222
Cooling Water Flow Rate (m^3/h)	375
HT Hot Water Flow Rate (m^3/h)	42
LT Hot Water flow rate (m^3/h)	52.5
Inlet Chilled Water temperature (^oC)	12
Outlet Chilled Water temperature (^oC)	7
Inlet Cooling Water temperature (^oC)	32
Outlet Cooling Water temperature (^oC)	37.5
Inlet HT Hot Water temperature (^oC)	173
Outlet HT Hot Water temperature (^oC)	160
Inlet LT Hot Water temperature (^oC)	86
Outlet LT Hot Water temperature (^oC)	78.5
Cooling Tower Capacity (kW)	2395

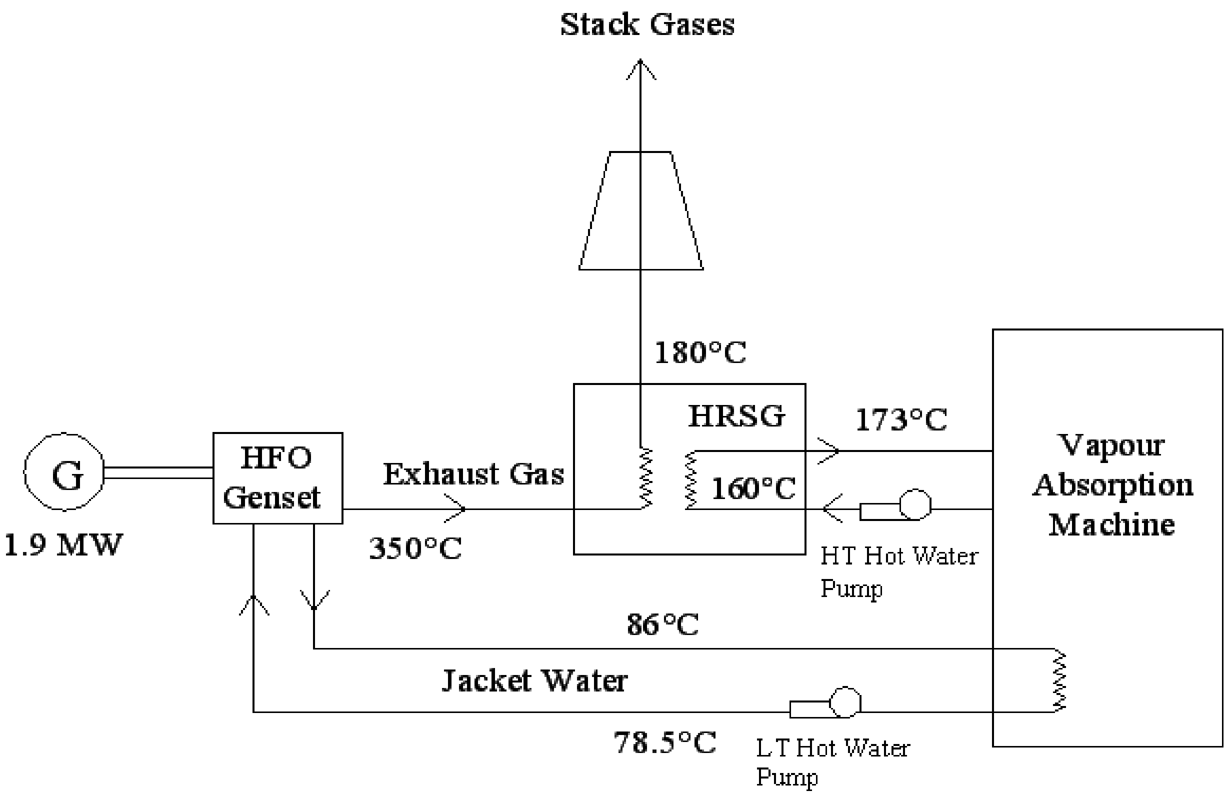

Figure 1. Schematic diagram of HFO based building cogeneration system

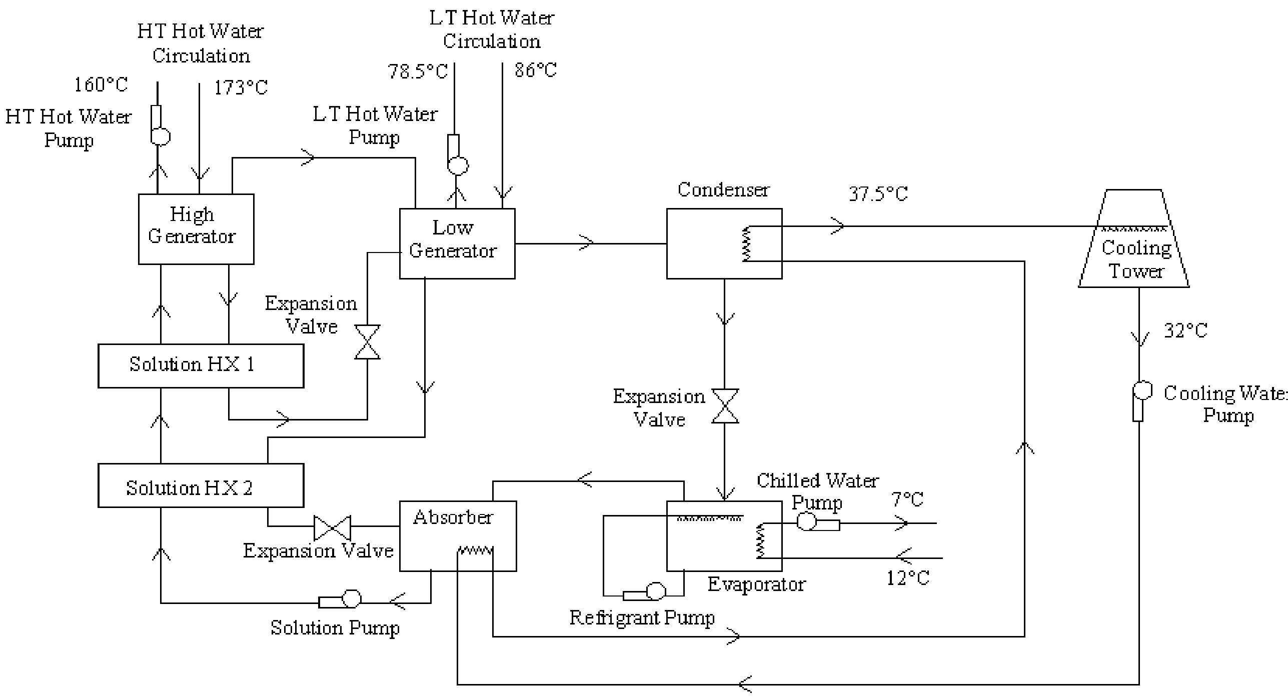

Figure 2. Schematic diagram of VARS system

Figure 2. shows schematic diagram of VARS uses lithium bromide and water as working fluids. The high temperature hot water generated in the HRSG by heat energy from exhaust gases is used to heat the solutions of high-pressure generator and produce water vapour. Water vapour then enters the low-pressure generator of the VARS. The jacket water directly enters the low-pressure generator to drive refrigeration cycle. Chilled water for building air-conditioning is supplied from evaporator of the VARS.

3. COST ANALYSES OF AIR-CONDITIONING SYSTEMS

A fair comparison of two alternative air-conditioning systems i.e., VCRS and VARS are made wherein the capacity of both the systems are same. The type of VCRS used for comparison is a high efficiency screw chiller of a rated capacity of 375 TR. Here a DEVARS is compared against a high efficiency screw chiller. The heat rejection equipment for VARS and VCRS is considered in this work is cooling tower with a capacity of 2395 kW and 1597 kW respectively.

The following sections present details of how the various costs are evaluated.

3.1 Initial costs

Initial costs of the VARS includes double effect absorption chiller, cooling tower, cooling water pump, chilled water pump, LT and HT hot water pump.

The initial cost of the VCRS includes high efficiency screw chiller, cooling tower, cooling water pump and chilled water pump. The cooling tower capacity for the VARS is 1.5 to 2 times larger than that of VCRS for same chiller capacity.

The cost of air handling unit and other auxillary equipment includes fan motors and water treatment system for the cooling tower. The difference in these costs between the two systems can be assumed to be zero.

As can be seen from Table 2, an initial cost of VARS is 125% higher than that of VCRS.

Table 2 Initial cost of VARS and VCRS

Unit	Initial cost ($)	
	VARS	VCRS
Machine cost ($)	278478	112041
Cooling tower ($)	22826	19565
Cooling water pump ($)	5435	4348
Chilled water pump ($)	3913	3913
LT hot water pump ($)	1848	
HT hot water pump ($)	1848	
Total initial cost ($)	314348	139868

3.2 Operating costs

Operating costs include the cost of power generation and cost of electricity. Annual operating hours for VARS and VCRS is 8760.

Table 3
Power required for VARS and VCRS

Unit	Power data (kW)	
	VARS	VCRS
Refrigerant pump	1.5	
Solution pump	7	
Compressor power		335.5
Cooling water pump	37	30
Chilled water pump	37	37
LT hot water pump	5	
HT hot water pump	5	
Cooling tower fan	15	10
Total power input	107.5	412.5

Here the cost of VARS is operated by waste heat from exhaust gases and jacket water is zero.

Table 4
Annual operating costs of VARS and VCRS
Unit Cost of power generation = $0.108
Unit cost of electricity = $0.13

Unit	Operating costs ($)	
	VARS	VCRS
Refrigerant pump		
Total use (kWh/y)	13140	
Annual cost ($)	1428	
Solution pump		
Total use (kWh/y)	61320	
Annual cost ($)	6665	
Compressor power		
Total use (kWh/y)		2938980
Annual cost ($)		383345
Cooling water pump		
Total use (kWh/y)	324120	262800
Annual cost ($)	35230	34278
Chilled water pump		
Total use (kWh/y)	324120	324120
Annual cost ($)	35230	42277
Cooling tower fan		
Total use (kWh/y)	131400	87600
Annual cost ($)	14283	11426
LT hot water pump		
Total use (kWh/y)	43800	
Annual cost ($)	4761	
HT hot water pump		
Total use (kWh/y)	43800	
Annual cost ($)	4761	
Total annual operating cost ($)	102359	471326

But the power input for pumps which are including in VARS from HFO fuelled 1.9 MW cogeneration system.

Electrical operating costs for the VARS comprise the solution pump, refrigerant pump, cooling water pump, chilled water pump, cooling tower fan, LT and HT hot water pump. The operating costs of VARS is mainly depends upon the unit cost of power generation (UCPG) in cogeneration system.

Annual operating cost of the VARS was calculated using the following equation:

$$O^y\,(VARS) = n_y * UCPG_{cogen} * TP_{VARS} \qquad (1)$$

With regard to the VCRS, the operating costs are dominated by the electricity required to drive the compressor. Additional electricity is used to drive the cooling water pump, chilled water pump and cooling tower fan.

Annual operating cost of the VCRS was calculated using the following equation:

$$O^y\,(VCRS) = n_y * EC * TP_{VCRS} \qquad (2)$$

3.3 Maintenance costs

The VARS are more reliable and have lower maintenance costs than VCRS because they have fewer highly-stressed moving parts.

The maintenance costs of VARS and VCRS are labor and material expense required to maintain system in suitable use condition. The total annual maintenance cost of VARS and VCRS are US $6522 and US $9348 respectively.

3.4 Replacement costs

The replacement costs of VARS include solution pump, refrigerant pump, cooling water pump, chilled water pump, LT and HT hot water pump. For VCRS, the replacement costs include cooling water pump and chilled water pump.

The pumps which include in both systems are replaced twice for an analysis period. Cost of cooling towers and chillers are not including in the replacement cost because the life time of cooling towers and chillers are same as analysis period. The service life for all the pumps is 10 years. Chapter 1, Owning and Operating costs, of the 1999 ASHRAE handbook – Applications contains an estimate of service lives of pumps. Table 5 shows the replacement costs for VARS and VCRS.

Table 5
Replacement costs of VARS and VCRS

Unit	Replacement cost ($)	
	VARS	VCRS
Solution pump ($)	10870	
Refrigerant pump ($)	6522	
Cooling water pump ($)	5435	4348
Chilled water pump ($)	3913	3913
LT hot water pump ($)	1848	
HT hot water pump ($)	1848	

3.5 Salvage values

The Salvage values of VARS and VCRS are the estimated value of the systems at the end of the useful life.

Here the salvage value of the each system after 23 years is estimated by assuming 5% of total initial costs of each system. Salvage values of VARS and VCRS are US $21685 and US $7505 respectively.

4. LIFE CYCLE COST ANALYSES OF AIR-CONDITIONING SYSTEMS

A LCCA was carried out to compare the VARS and VCRS. The system service lives of the VARS and VCRS expected to be same, and it was taken as 23 years. Chapter 1, Owning and Operating costs, of the 1999 ASHRAE handbook – Applications contains an estimate of service lives of systems. The analysis is based on PWC method, a discount rate of 8% is used to calculate the PWC of initial costs, operating costs, maintenance costs, replacement costs and salvage values of each system over an analysis period.

The following equation is used to calculate the PWC of operating costs and maintenance costs.

$$P = A \left[\frac{(1+d)^N - 1}{d(1+d)^N} \right] \quad (3)$$

The following equation is used to calculate the PWC of replacement costs and salvage values.

$$P = F \left[\frac{1}{(1+d)^N} \right] \quad (4)$$

The following equation is used to calculate the life cycle cost using PWC method.

$$LCC = \text{Initial costs} + P_O + P_M + P_{RE} + P_{SV} \quad (5)$$

5. RESULTS

The results of LCCA are presented in Table 6. The analysis described an economic technique for evaluating the systems. This technique has been used to examine all the costs of two alternatives over the analysis period in terms of their PWC. The total LCC of the VARS was US $ 1.5 million compared US $5.1 million for the VCRS. The LCC of VARS has an approximated cost advantage of 71.5 % over the VCRS.

Table 6
Life cycle cost of VARS and VCRS

Unit	LCC ($)	
	VARS	VCRS
Initial Cost ($)	314348	139868
PWC of annual operating cost ($)	1061568	4888151
PWC of annual maintenance cost ($)	67637	96947
PWC of solution pump ($)	7367	
PWC of refrigerant pump ($)	4420	
PWC of cooling water pump ($)	3683	2947
PWC of chilled water pump ($)	2652	2652
PWC of LT hot water pump ($)	1252	
PWC of HT hot water pump ($)	1252	
PWC of salvage value ($)	3693	1278
Discount rate (%)	8	8
Life span (years)	23	23
Life Cycle Cost ($)	1460486	5129287

The VARS is more expensive to install, has considerably lower operating and maintenance costs than VCRS.

The financial indicator, Internal Rate of Return (IRR) for VARS over VCRS has been calculated by varying Net Present Value (NPV) with respect to discount rate in the Figure 3 is 88.63 %.

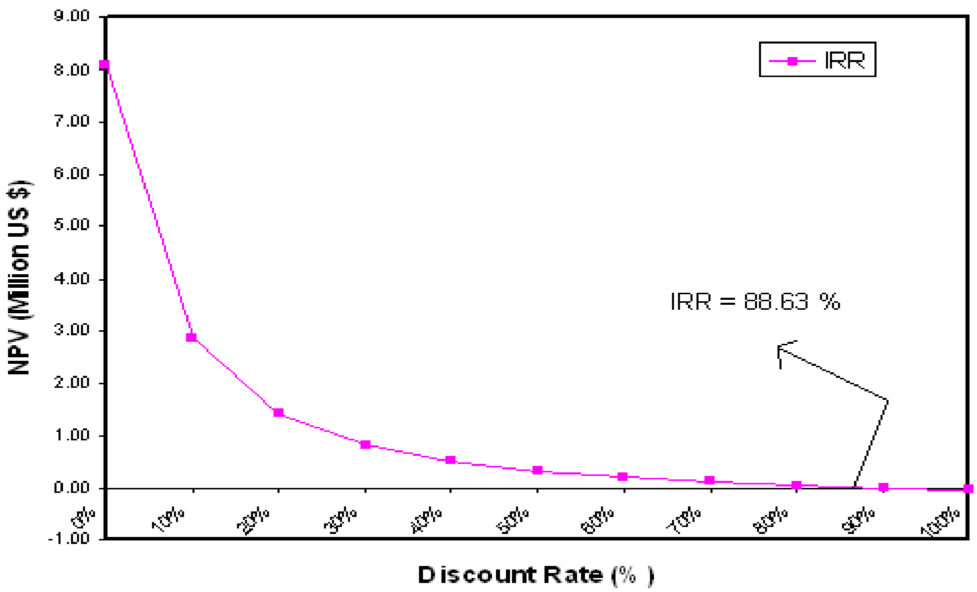

Figure 3. Variation of NPV with respect to Discount Rate

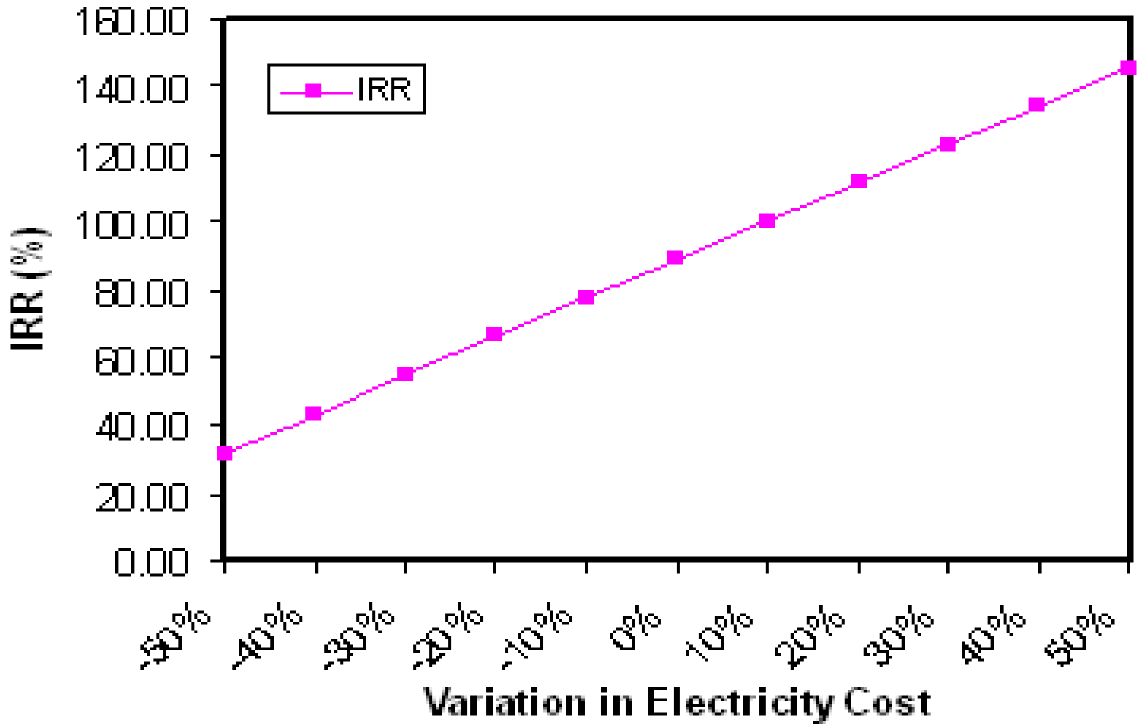

Figure 4. Sensitivity analysis of IRR with respect to electricity cost

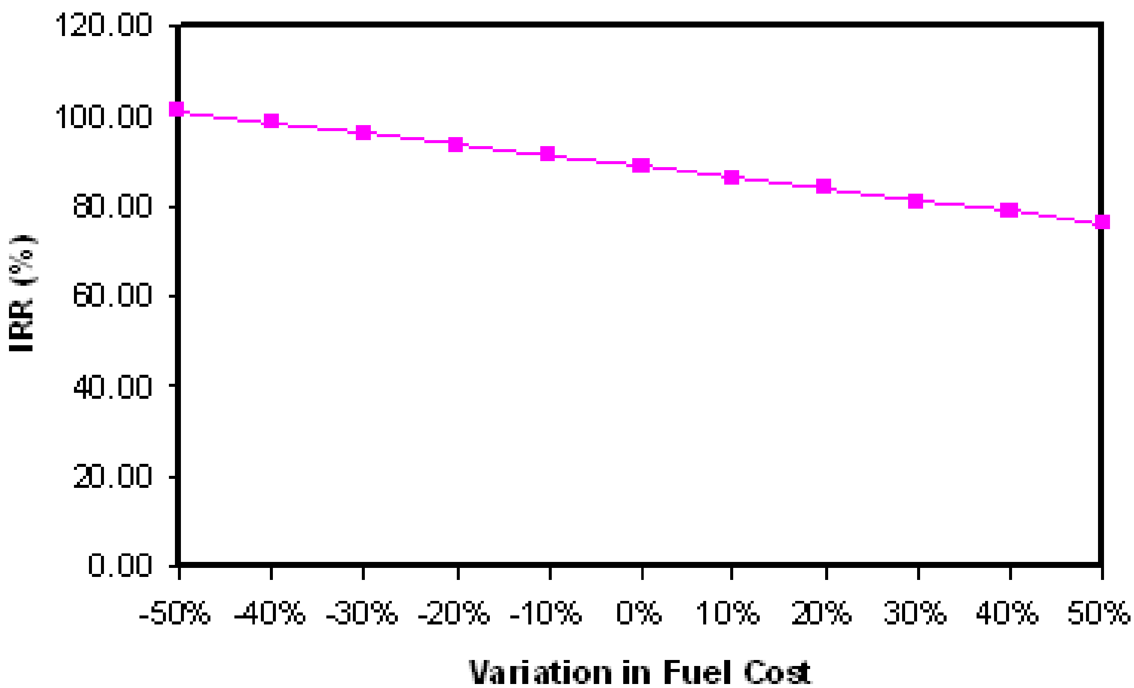

Figure 5. Sensitivity analysis of IRR with respect to fuel cost

Sensitivity analysis also made for IRR with respect to electricity and fuel cost are varying from -50 % to 50 %.

Figure 4 shows variation in IRR with respect to electricity subjected to the conditions that the fuel cost kept constant. It was observed that the IRR increases linearly by increasing electricity cost. The variation in the IRR with respect to fuel cost subjected to the conditions that the electricity cost kept constant is shown in Figure 5. It was observed that the IRR decreases gradually by increasing fuel cost.

The results shows that the waste heat operated VARS promises to be desirable alternative for building HVAC application.

6. CONCLUSION

In this paper, life cycle cost analysis of waste heat operated vapour absorption air conditioning system (VARS) incorporated in a building cogeneration system is presented and the same is compared with the electric based vapour compression chiller (VCRS) of same capacity. Initial cost of VARS is high and operating cost of VARS is low when compared with VCRS. LCC is mainly depends upon operating costs. From the analysis, it was found that the initial cost of VARS was 125 % higher than that of VCRS, while the PWC of operating cost of VARS was 78.2% lower compared to VCRS. The results showed that the life cycle cost (LCC) of waste heat operated absorption chiller is estimated to be US $1.5 million which is about 71.5 % low compared to electric powered conventional vapour compression chiller. In addition, VARS systems will result in GHG reduction of 2.85×10^6 kg/y.

The deviation in the life cycle cost of the two systems where analyzed by plotting suitable graphs (IRR). The result shows that the waste heat operated VARS would be preferable from the view point of operating cost and maintenance cost.

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