Economic Analysis Of Combined Solar-Assisted Ejector Absorption Refrigeration System

J. M. Abdulateef, Nurul Muiz Murad, M. A. Alghoul, A. Zaharim and K. Sopian

***Abstract*—** A procedure is presented for assessing the economic viability of combined solar-assisted ejector absorption refrigeration system in terms of the life cycle savings function. The optimization is carried out for a combined system that has been designed for Malaysia and similar tropical regions using ammonia-water as working fluid. The life cycle savings is expressed in a generalized form in terms of two economic parameters, P_1 and P_2, which relate all life cycle cost considerations to the first year fuel cost or the initial solar system investment cost. The typical meteorological year file containing the weather parameters for Malaysia is used to calculate the monthly average daily radiation and solar fraction. An example for economical evaluation and optimization is presented. The optimum system for Malaysia's climate for a 5 kW (1.5 refrigeration ton) system consists of 35 m^2 evacuated tubes solar collector sloped at 15^o.

***Keywords*—** Ejector; Economic analysis; Life cycle; Absorption.

I. INTRODUCTION

SOLAR cooling technology for air-conditioning and refrigeration applications has received increasing interests as an environmental-friendly and sustainable alternative. A majority of research and development studies regarding solar-driven ejector refrigeration systems deal with the single stage system type[1-4].

The economic analysis of solar energy systems is carried out in order to determine the least cost of meeting the energy needs, considering both solar and non-solar alternatives. The method employed for the economic analysis is called the life savings analysis. This method takes into account the time value of money and allows detailed consideration of the complete range of costs.

All software programs like TRNSYS, WATSUN, Polysun and *F*-Chart as well as artificial neural networks applied in solar energy systems modelling and prediction have routines for the economic analysis of the modeled systems [5]. The economic analysis of solar systems can also be performed with a spreadsheet program. Spreadsheet programs are especially suitable for economic analyses as their general format is a table with cells which can contain values or formulae and they incorporate many built-in functions. A detailed description of the method of economic analysis of solar systems using spreadsheets is given in Ref. [6].

In the present work, the economic analysis of 5 kW solar-driven ejector absorption refrigeration system using ammonia-water is presented. The calculation procedure in the present study is carried out by using a spreadsheet application (Microsoft Excel).

II. ECONOMIC ANALYSIS AND OPTIMIZATION

Several methods for economical analysis of solar systems are presented in detail in Duffie and Beckman [7]. Among them, the life cycle cost savings method (LCS) has shown to be a simple and practical method to derive the optimization function in terms of the basic costs of the system, the load, and the design parameters.

Fig. 1 shows a combined solar-driven absorption refrigeration system with a 5 kW cooling capacity. The system was installed in Bangi, University Kebangsaan Malaysia on the roof of the physics department, labs of Science Faculty.

The solar fraction, defined as the ratio of solar-supplied heat to total thermal load, is dependent on available solar radiation, collector efficiency, collector surface area, and thermal load. The cost of solar-assisted cooling cycles is therefore linked to the solar fraction, which determines the optimal collector area, and the cost of operating an auxiliary heating system.

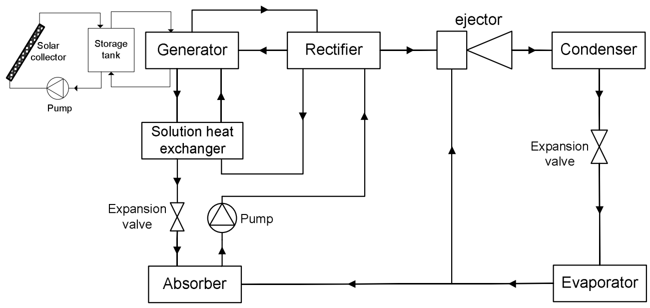

Fig. 1. Schematic diagram of combined solar-assisted ejector absorption refrigeration system

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The life cycle savings of a solar absorption cooling system over a conventional system can be expressed as the difference between a reduction in fuel costs and an increase in expenses incurred as a result of the additional investment for the solar system [7].

$$LCS = P_1.C_F.L.F - P_2.C_s \qquad (1)$$

and

$$C_s = C_A.A_c + C_E \qquad (2)$$

where LCS is the life cycle savings of solar combined system over a conventional system, \$; C_F the unit cost of delivered conventional energy for the first year of analysis, \$-GJ^{-1}; L the annual load, GJ; F the annual fraction of load supplied by solar energy; C_s the total cost of installed solar energy equipment, \$; C_A the solar energy system investment cost which directly proportional to collector area include such items as the purchase and installation of the collector and a portion of storage costs, \$-m^{-2}; A_c the collector area, m^2; C_E the solar energy system investment costs which are independent of collector area, \$; P_1 the factor relating life cycle fuel cost savings to first year fuel cost savings and P_2 the factor relating life cycle expenditures incurred by additional capital investment to the initial investment.

The multiplying factors, P_1 and P_2, facilate the use of life cycle cost methods in a compact form. Any cost which is proportional to either the first year fuel cost or the initial investment can be included.

To illustrative the evaluation of P_1 and P_2, consider a very simple economic situation in which the only significant costs are fuel and system equipment costs. Assume that the fuel costs escalate at a constant annual rate, and the owner pays cash for the system at the begining of the analysis. Here, P_1 accounts for fuel escalation and the discounting of future payaments. The factor P_2 accounts for investment related expenses which, in this case, consist only of the investment. Since the investment is already expected in current dollars, P_2 is unity for this example. The factor P_1 and P_2 are then:

$$P_1 = PWF(N_e, i, d) \qquad (3)$$

$$P_2 = 1 \qquad (4)$$

where d is the annual market discount rate, i the annual market rate of fuel price escalation and N_e the years of economic analysis. The function $PWF(N_e,i,d)$ is defined as:

$$PWF(N_e, i, d) = \frac{1}{d-i}[1 - (\frac{1+i}{1+d})^{N_e}] \qquad (5)$$

The function $PWF(N_e,i,d)$ is a present worth factor that accounts for inflating payments in discounted money. When multipliyed by a first period cost (which is inflated at a rate, i, and dicounted at a rate, d, over N_e periods), the resulting value is the present worth life cycle cost. Each payment is assumed to be made at the end of the period and the present worth of the series of payments is as of the beginning of the first period. When the infaltion rate is zero, $[PWF(N_e, 0,d)]^{-1}$ is the capital recovery factor.

A more complex analysis may be formulated to included a wide varity of expenses so that P_1 and P_2 take the following forms:

$$P_1 = (1 - C\bar{t})PWF(N_e, i, d) \qquad (6)$$

$$P_2 = D + (1-D)\cdot\frac{PWF(N_{\min},0,d)}{PWF(N_L,0,m)} - \bar{t}.(1-D)$$
$$.[PWF(N_{\min}, m, d)\left(m - \frac{1}{PWF(N_L,0,m)}\right)$$
$$+\frac{PWF(N_{\min},0,d)}{PWF(N_L,0,m)}] + (1-C\bar{t})M_s \cdot PWF(N_e, g, d) \qquad (7)$$
$$+(1-\bar{t}).tV.PWF(N_e, g, d) - \frac{C\bar{t}}{N_D}PWF(N'_m,0,d)$$
$$-\frac{R_v}{(1+d)^{N_e}}(1-C\bar{t})$$

where C is the commercial or non-commercial flag (1 or 0, respectively); m the annual mortgage interest rate; g the general inflation rate; N_L the term of loan; N_{min} the years over which loan payments contribute to analysis; N_D the depreciation lifetime; N'_{min} the years over which depreciation deductions contribute to analysis; $\bar{t}$ the effective income tax rate; t the property tax rate base on assessed value; D the ratio of down payment to initial investment; M_s the ratio of first year miscellaneous costs to initial investment; V the ratio of assessed value in first year to initial investment and R_v the ratio of salvage or resale value to initial investment. All other terms are as previousal defined.

In the expression for P_2 of equation (7), the first term represents the down payment; the second term represent the life cycle cost of the mortgage principal and interest; the third, income tax deducations of the interest; the fourth, miscellaneous costs (maintenance, parasitic power, insurance, etc.); the fifth, net property tax costs; the sixth, straight line depreciation tax deducation; the seventh, salvage or resale value. These and other terms may be added to or deleted from an analysis, allowing a range of economic complexity.

For a given location, annual load, and economic situation, it is possible to optimize the system design variables to yield the maximum life cycle savings. The maximum life cycle savings, and hence the optimum collector area, is characterized by the point at which the derivative of the life cycle savings with respect to collector area is zero.

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$$\frac{\partial(LCS)}{\partial A_c} = 0 = P_1.C_F.L\frac{\partial F}{\partial A_c} - P_2.C_A \qquad (8)$$

Rearranging, the maximum savings are realized when the relationship between collector area and the fraction of load supplied by solar satisfies the following:

$$L\frac{\partial F}{\partial A_c} = \frac{P_2.C_A}{P_1.C_F} \qquad (9)$$

Since the load is constant through the optimization, it can be incorporated into the derivative to give at the optimum:

$$\frac{\partial F}{\partial(A_c/L)} = \frac{P_2.C_A}{P_1.C_F} \qquad (10)$$

By employing the assumption that the load distribution depends only on location, F can be expressed as a function of location, collector characteristics, and the ratio A_c/L. Equation (10) then implies that, for a given location and collector type, the area to load ratio at which maximum savings can be achieved is a unique function of one economic parameter, $P_2.C_A/P_1.C_F$.

III. Results and Discussion

The example chosen here for the location of Bangi, Selangor (ϕ=3.1^o) is given in Appendix A. The cooling capacity is taken to be 5 kW for 12 h of operation each day of the year. The values of $F_R(\tau\alpha)$ and F_RU_L for the evacuated tube collector are 0.7 and 3.3 W/m^2 ^{o}C respectively [8]. Collectors' inlet temperature could be commonly taken as 10 ^{o}C greater than generator temperature. The *COP* for the absorption system is equal to 0.65 as found from data of Abdulateef [9] for T_{gen}= 75 ^{o}C, T_{cond}= 25 ^{o}C, T_{abs}=25 ^{o}C and T_{evp}=-2 ^{o}C.

Table 1 shows the monthly average ambient temperature and the monthly average daily radiation incident on the collector surface per unit area were obtained from the information supplied by the typical meteorological year file containing the weather parameters for Malaysia with optimum collector slope angle around 15^o.

Table1. Monthly average daily radiation

Month	T_{amb} (^{o}C)	$\overline{H}$ (MJ/m^2)	$\overline{H}_T$ (MJ/m^2)
Jan	26.9	13.743	14.629
Feb	27.12	15.963	16.56
Mar	27.8	18.474	18.495
Apr	27.14	18.197	17.369
May	27.8	16.464	15.165
Jun	27.4	15.148	13.761
Jul	26.7	14.633	13.444
Aug	27.05	15.511	14.656
Sep	26.3	15.891	15.635
Oct	26.4	16.744	17.216
Nov	25.8	13.929	14.726
Dec	25.9	13.607	14.61

Different collector areas were used in order to obtain the optimal sizing of the system. Fig. 3 shows the monthly variation of solar fraction for different solar collector areas. As can be seen the maximum solar fraction can be obtained in March and April.

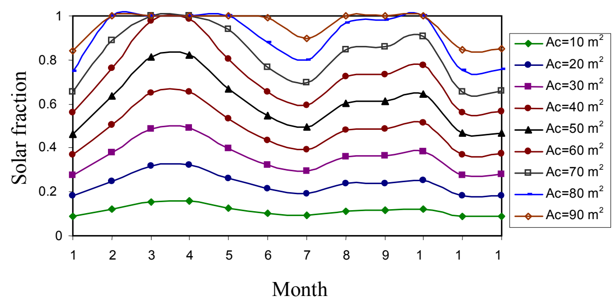

Fig. 3 Monthly variation of solar fraction for different solar collector areas

Fig. 4 shows the variation of annual solar fraction for different collector areas. It is seen that the solar fraction increases with collector area. For collector areas bigger than about 35 m^2 there is no sensible change in solar fraction.

Table 2 shows the relationship between collector area and annual solar fraction in the first two columns. The total system costs, shown in the third column. Column 4 includes the present worth of solar savings, calculated over a 10-year period, the expected lifetime of the equipment. A calculation is made for a very small collector area where the cost of the system is essentially C_E, to establish the "zero area" solar savings.

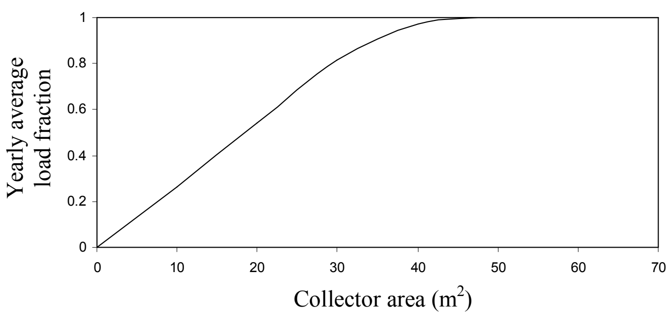

Fig. 4 Variation of annual solar fraction for different collector areas

Table 2. Live cycle savings calculations

A_c (m^2)	Solar Fraction(F)	Installation cost (USD)	Solar Savings (USD)
0.01	0	3253.8	-2820.43
10	0.266	7000	-982.201
20	0.543	10750	1064.119
25	0.681	12625	2087.279
30	0.813	14500	2969.197
35	0.917	16375	3335.263
40	0.972	18250	2765.205
50	1	22000	52.59809
60	1	25750	-3197.99

Life cycle solar savings as a function of collector area are plotted in Fig. 5. The curve of Fig. 5 begins with a negative savings for zero collector area. The magintude of this loss is equal to $P_2.C_{E,}$ and reflects the presence of solar energy system fixed costs in the absence of any fuel savings. As a collector area increases, the curve show increased savings until reaching a maximum at some optimum collector area. As the collector area is further increased, the fuel savings continuo to increase, but the excessive system costs force the solar savings to decrease.

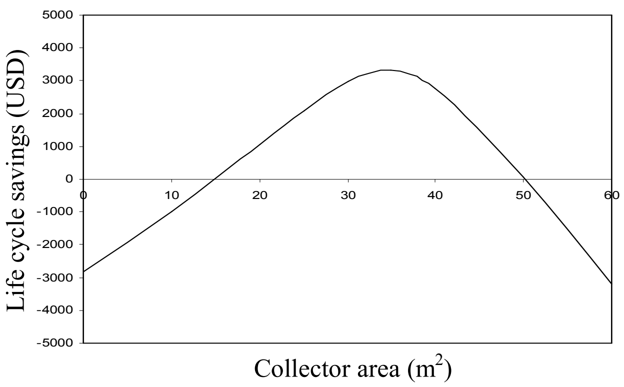

Fig. 5. Life cycle savings vs. collector area

The maximum solar savings from the solar cooling system compare to the conventional system is USD 3335. The maximum solar savings are realized at a collector area of about 35 m^2, and positive savings are realized over an area range of approximately 20 to 50 m^2. The specifications of the final system obtained from the optimization study are shown in Table 3.

Table 3. The final system specification

Collector type	Evacuated tube
Unit capacity	1.5 ton (5 kW)
Collector area	35 m^2
Collector slope (β)	15^o

IV. CONCLUSIONS

Economical evaluation and optimization of thermally driven ejector cooling cycles assisted by solar energy is presented. The method used in this paper allows the individual architect or engineer to design an economically optimal solar cooling system and evaluate the economic comparison with an alternative conventional system. Life cycle cost analysis with two parameters, P_1 and P_2, is used for economic evaluation. The use of these parameters requires one economic assumption: all costs which contribute to the life cycle costs of the solar cooling system or conventional system are directly proportional to either the first year fuel cost or the initial solar system investment. The final optimum system as obtained from the economic optimization consists of 35 m^2 evacuated tube collector tilt at 15^o from horizontal. The prospects of solar cooling are expected to further improve with the growth of solar industry and the escalation of fuel cost.

Nomenclature

A_c collector area (m^2)
COP coefficient of performance
F annual solar fraction
F_R collector heat removal factor
$\overline{H}$ monthly average daily radiation on the horizontal collector surface (MJ/m^2)
$\overline{H}_T$ monthly average daily radiation on the tilted collector surface (MJ/m^2)
LCS life cycle savings (US$)
L annual load (GJ)
P_1 ratio of life cycle fuel savings to first year fuel energy cost
P_2 ratio of owning cost to initial cost
T temperature (^oC)
U_L collector overall loss coefficient ($W/m^2 {}^oC$)

Greek symbols

β tilt angle of solar collector
ϕ latitude angle
$(\tau\alpha)$ transmittance absorptance product

Subscripts

amb ambient
abs absorber
cond condenser
evp evaporator
gen generator

APPENDIX

A. Economic calculations

For the present example, the proposed collector and associated equipment to be financed over 10 years at an interest of 9%. The cooling capacity is 5 kW for 12 h of

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operation per day, and a seasonal *COP* of 0.65 was considered for the absorption system. The load is 120 GJ/year. The first year's electricity cost for a system without solar would be $2000, was expected to rise at a rate of 5% per year. The market discount rate was expected to be 8% through the period of analysis. The effective income tax considered was 45%.

Area dependent cost is $375/m^2$, and the area-independent cost (fixed cost) is $3250. The down payment is one-six of the cost. Assume that maintenance and cost of parasitic power are negligible and there is no property tax on the solar equipment. It is expected the equipment will have no resale value at the end of 10 years of the original cost (R_v=0). Assume that all payments are made at the end of the year in which they are incurred. The relationship between collector area and annual solar fraction is shown in the first two columns of Table 2.

The costs of the solar energy system are calculated by equation (2), with C_A=$375/m^2$ and C_E= USD 3250. The third column in Table 2 indicates the total system cost. The first year's electricity cost for a system without solar would be $C_F.L$=2000 $/year. The installation is not an income-producing one so C=0. The ratio P_1 is calculated from equation (6):

$$P_1 = \text{PWF}(10,0.05,0.08) = 9.5614$$

The ratio P_2 is calculated from equation (7):

$$P_2 = 0.167 + 0.833 \cdot \frac{PWF(10,0,0.08)}{PWF(10,0,0.09)} - 0.45 * 0.833 \cdot [PWF(10,0.09,0.08)\left(0.09 - \frac{1}{PWF(10,0,0.09)}\right) + \frac{PWF(10,0,0.08)}{PWF(10,0,0.09)}] = 0.867$$

From equation (10) with C_A=$375/m^2$ and $C_F.L$= USD 2000.

$$\frac{\partial F}{\partial A_c} = \frac{P_2.C_A}{P_1.C_F.L} = 0.0170$$

The optimum collector area, where the slope is 0.017 is about 35 m^2, see Figure 4, and the maximum solar savings is USD 3335.

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