Research Article

Cost-effectiveness of Solar Cooling for Office and Hypermarket

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Abstract

Air-conditioning consumes electricity intensively in Thailand and it is desirable to investigate if less intensive means of cooling is viable. This paper presents results of assessment of financial viability of application of solar cooling employing single-effect absorption chiller to a large office building model and a hypermarket model under Thai context. The well-known TRNSYS program is used to simulate operation of solar cooling system in the two building models under a solar autonomous mode and an electric chiller-assisted solar cooling mode. Multiple simulation runs with variation on the size of hot water tank and solar collector area were conducted to obtain the solar autonomous configuration and the electric chiller-assisted configuration that offers lowest life cycle cost (LCC) for each building type. The LCCs for both types of buildings under electric chiller-assisted mode at optimum configuration are lower than that from electric cooling. Payback periods for optimum solar cooling mode are all positive for both building types, although relatively long, at 24 and 26 years. If solar equipment is subsidized under a 30/70% scheme, payback periods could be reduced to 14 and 16 years. The prospect for solar thermal cooling is positive.

Keywords: Assessment of financial, Solar cooling, Single-effect absorption chiller, TRNSYS

1 Introduction

Thailand is in a tropical region and air-conditioning is now used in all large commercial buildings. Commercial buildings are responsible 23% of total electricity consumption in Thailand [1]. Air-conditioning contributes to 60% of total electricity consumption of a building [2]. Electric vapor compression system is commonly used. Electric cooling contributes to indirect emission of carbon dioxide, at power plants, and the refrigerant used, hydrochlorofluorocarbons (HCFCs), also contributes as greenhouse gas.

Solar cooling is a possible alternative means of cooling that will minimally contribute to emission of

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greenhouse gas. This paper will consider only application of solar thermal cooling to large commercial buildings. Thailand has high solar irradiance, at annual average of 18.2 MJ/m^2/day, [3]. The Ministry of Energy has the foresight of planning to utilize solar cooling in the Plan for Development of Alternative Energy 2015–2036 (AEDP 2558–2579). The plan sets a target to promote the use of 300,000 m^2 of solar cooling, [4]. Solar photovoltaic (pv) cooling is another option of solar cooling that has only received attention recently due to availability of low cost pv panels, [5].

Pongtornkulpanich *et al*. [6], describes a solar cooling system at the School of Renewable Energy Technology (SERT) in Naresuan University, Thailand. The system comprises 72 m^2 of evacuated tube collectors, 35 kW of absorption chiller, 0.5 m^3 of hot water tank, 0.2 m^3 of chilled water tank and an LPG gas unit for backup. The capital cost of the absorption chiller and the solar collector array dominated the project budget. Balghouthi *et al*. [7] simulated and studied to select and size the different components of solar cooling system to be installed in Tunisia. The optimized system for a typical building of 150 m^2 comprised of an absorption chiller of 11 kW, 30 m^2 of flat plate collector, which is inclined at 35 degrees from the horizontal plane, 0.8 m^3 of hot water tank. Calise *et al*. [8] simulated and analyzed three configurations of solar cooling system that is used in an office building in the south of Italy. In this research, the configuration comprises of an electric water-cooled chiller as a back-up system has higher performance than the configuration uses a gas-fired heater. Agyenim *et al*. [9] conducted an experimental solar cooling system in Cardiff University. The system including a 12 m^2 of vacuum tube collector, a 4.5 kW of absorption chiller, and a 1 m^3 chilled water storage tank. The coefficient of performance of this system is 0.58. Most of the cited papers analyzed performance of small-size solar cooling systems using hot water boiler as backup. Economical or financial viability is not dealt with. Ma *et al*. [10] compared feasibilities of application of three solar air-conditioning systems with auxiliary heat source for an office building of 2,004 m^2 in eight cities in Australia using an electric system as reference. The payback periods of solar absorption cooling system are between 13 and 24 years among the eight cities. Bellos and Tzivanidis [11] use TRNSYS to simulate application of solar-fired single-effect absorption cooling with auxiliary heat source for a 100 m^2 office in ten cities in the world. The authors report resulting minimum solar collector area, tank size, and levelized cost applicable to each city. It is concluded that locations with high cooling loads and solar potentials are suitable for solar cooling.

In this research, an office and a hypermarket building model each requiring an estimated cooling load of 500 RFT (refrigeration tons) or 1,760 kW_{th} are used for a study on financial viability of application of single-effect solar thermal cooling in Thailand. This size is chosen so that the cost of such absorption cooling system is comparable to that of an electric vapor compression system, as illustrated in [12]. Two modes of operation of solar cooling system in each building model are considered, solar autonomous mode and electric chiller-assisted mode. These will be described in details in the next section. The study utilizes TRNSYS as the simulation tool. Although simulation analysis cannot fully replicate the varying operating conditions faced in physical experiments, simulation using computational tools whose algorithms are derived from and closely follow the physical phenomena they represent is the most accurate means. Moreover, simulation allows use of a variety of system components of different sizes that are costly and time-consuming to assemble in physical experiments.

2 Methodology

Before proceeding, there is a need to define operating time of the 'office' as well the 'hypermarket' building models. An office building that is amenable to application of solar cooling should be low-rise. In order to enhance financial viability of solar cooling, a solar cooling system is assumed operated for every day of a year. Table 1 lists the daytime duration and the total number of hours of solar cooling operation for each type of building. For hypermarket, electric cooling serves during 5.00 p.m.–10.00 p.m

Table 1: Daytime duration and total number of hours for each building model

Building Type	Daytime Operating Duration	Total Number of Hours in a Year
Office	08.00 a.m.–5.00 p.m.	3,285
Hypermarket	10.00 a.m.–5.00 p.m.	2,555

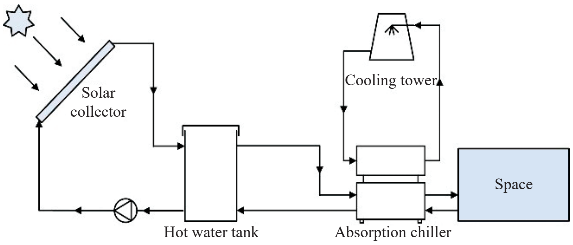

Figure 1: Minimal configuration.

2.1 *Minimal configuration of a solar cooling system*

A minimal configuration of a solar cooling system is depicted in Figure 1. It comprises a solar collector array of many panels, a hot water tank, an absorption water chiller that supplies chilled water directly to the load, and a cooling tower required by the absorption chiller. The minimum configuration would not include the hot water tank.

Because of the variability of solar radiation, a hot water tank can be used as a buffer to recirculate hot water through the solar collector array and increase temperature of water in the tank when solar radiation is strong. When solar radiation wanes, the stored hot water provides a buffer to supply hot water to operate the absorption chiller.

The minimum configuration does not have such buffer and the system will fail to operate for a large number of hours in a year.

Solar autonomous mode: By employing a sufficiently large array of solar collectors and a sufficiently large hot water tank, the minimal configuration can operate on the solar autonomous mode, i.e. the configuration can meet the load during specified daytime hours for every day throughout a year listed in Table 1.

Subsection 2.3 describes the use of TRNSYS simulation program to simulate operation of solar cooling systems in office and hypermarket models. The program was used to find the size of collector areas and the size of tanks required for solar autonomous operation for both building models. Section 3 presents results of simulation.

2.2 *External source-assisted configuration*

If the size of solar array or the size of the tank in the minimal configuration are insufficient, the minimal configuration will fail to operate for some hours. In order for such configuration with reduced array and reduced tank size to operate, external source of heat or external source of chilled water may be used to supplement the system to operate and meet load requirement for all hours in a year.

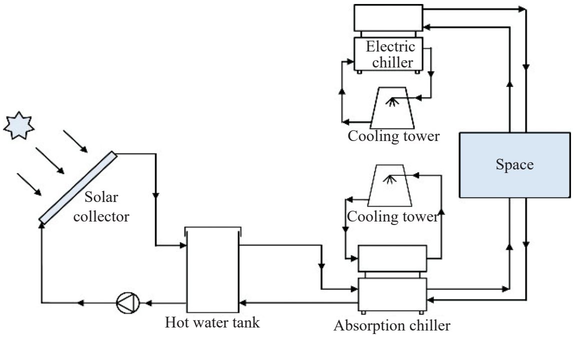

Figure 2: Configuration for operation in electric chiller-assisted mode.

One such external source is a boiler. A boiler can be used to raise hot water temperature to the level required to operate the absorption chiller. The use of a boiler brings up issues of safety, over-pressure and other protection arrangement, apart from costs and logistics in transportation of fuel(s). This option is not considered in this study.

Another alternative external source is the use of electric chiller to supply chilled water when the absorption chiller fails to supply required chilled water. Figure 2 shows this configuration.

Electric chiller-assisted mode: This electric chiller-assisted option is taken in this study. The absorption chiller may require a number of cooling towers, one of which is suitable for to be used with the electric chiller. Subsection 2.3 also describes the use of TRNSYS simulation program to simulate operation of solar cooling systems in the building models under this mode. The program was run for given size of collector areas and given size of tanks under this mode. Initial and operating costs were also obtained for each configuration eventually to find a configuration of lowest cost

2.3 *TRNSYS program*

TRNSYS program version 18 is used for simulation, its manual is referenced in [13]. The weather data file used is TH-Bangkok-484550.tm^2 which contains a typical meteorological year (TMY) data of Bangkok.

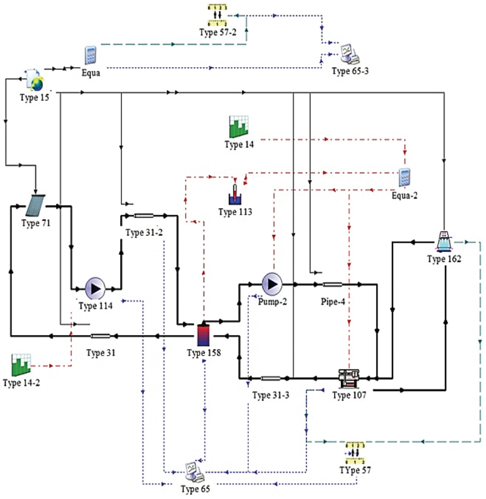

Figure 3: Solar cooling system program interface in TRNSYS.

The simulation interface used for simulating operation of solar cooling systems under the two modes defined in Subsection 2.1 and 2.2 is shown in Figure 3.

What appears as buttons with labels are program modules, each perform calculations in according to the function assigned to the module. Output information flows along the lines connecting the modules. The red lines carry control commands to operate the equipment at the destination. The blue-green lines carry status information to the destination module.

For a given hour, solar radiation and ambient air temperature data from the weather data file, type 15, at the top left corner of Figure 3, is supplied to activate the solar collector module, type 71, for it to heat up water that flows through it. Hot water is moved by the pump, type 114, to the tank, type 158. Hot water from the tank, type 158, is pumped to the absorption chiller, type 107. Condenser water flows from the absorption chiller to the cooling tower, type 162. Reference information on ambient air is supplied from the weather data file, type 15, to the cooling tower module, type 162, for it to operate to cool the condenser water.

The following describes algorithms used in pertinent modules.

2.3.1 Solar collector

The TRNSYS type 71, which is the module for evacuated tube collectors, is used. The module calculates temperature of water that flow through the collectors based on a quadratic efficiency relationship in the Equation (1), [14].

$$\eta = a_0 - a_1\left[\frac{T_{collector,in} - T_{amb}}{E}\right] - a_2\left[\frac{T_{collector,in} - T_{amb}}{E}\right]^2 \quad (1)$$

where a_0, a_1 and a_2 are the characteristic parameters of a solar collector,

E is the total solar radiation on the solar collector (W/m^2).

The values of the parameters used are $a_0 = 0.642$, a_1 = 0.89 W/m^2.K and a_2 = 0.001 W/m^2.K2 taken from a collector manufacturer, [15]. Evacuated tube collectors are chosen in the study here because they are suitable for operating at higher temperature and the use of hot water tank enhances storage and use of water at higher temperature.

2.3.2 Hot water storage tank

Module type 158 is a subroutine that models a constant volume storage tank. The algorithm is for a well-mixed tank. The thermostat in the tank allows hot water to flow to the absorption chiller when its temperature exceeds 70°C. The heat loss coefficient of the tank is 0.05 W/m^2.K, the specific heat capacity of water is 4.182 kJ/kg.K and the density of water is 992 kg/m^3.

2.3.3 Absorption chiller

Type 107, which is in the standard library. It accepts input data from performance curves of a chiller that a user chooses. Here a set of values of input hot water temperature, cooling water temperature, output chilled water temperature, with the corresponding value of cooling output and coefficient of performance (COP) constitute a set of data from the performance curves. Several sets of data from the performance curves of a single-effect absorption chiller, 1,760 kW$_{th}$ nominal cooling capacity of LG (LWM-021ET) are used. The model is marketed by LG Corporation, a Korean company. Selected performance curves from LG (LWM-021ET) are shown in Figure 4.

In this research, the absorption chiller will operate only when the inlet hot water temperature is higher than 70°C. Supply chilled water temperature of 7°C is chosen for the chilled water supply to the cooling

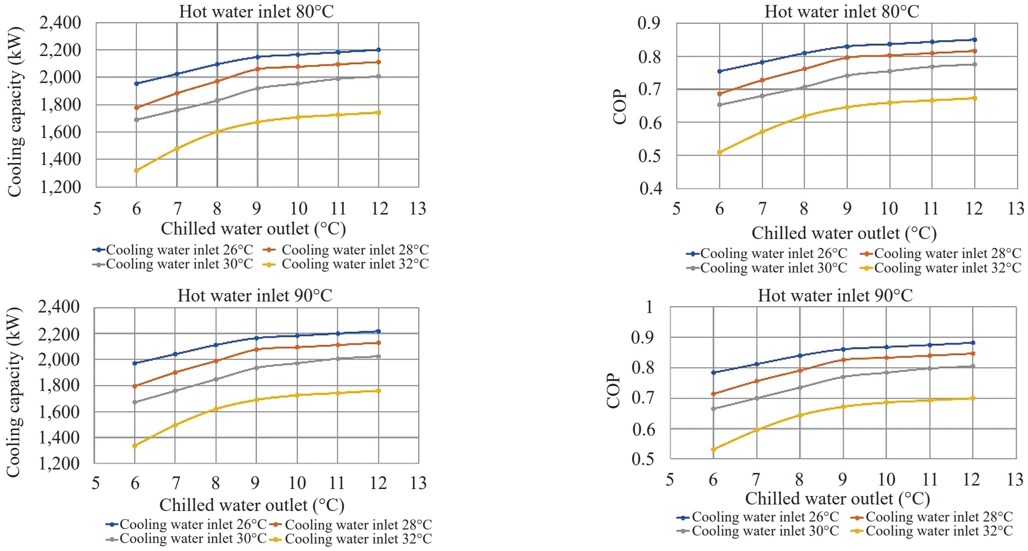

Figure 4: Performance curves of LG 1,760 kW_{th}(500-RFT) absorption chiller.

coil. Cooling output from TRNSYS matches the load in the space at the given chilled water temperature.

2.3.4 Pump

In this simulation, type 114 is used as single speed pump for circulating water in the solar collector loop with a mass flow rate of 12 kg/s. While for the absorption chiller loop, the mass flow rate is 23.67 kg/s.

2.3.5 Control function and thermostat

Type 14 or forcing function is used for setting the operation time of solar cooling system. For office building, the forcing function is fixed at 8.00 a.m.–5.00 p.m. While for hypermarket building, the forcing function is put at 10.00 a.m.–5.00 p.m. Type 113 is the thermostat that is used to control the hot water temperature in the tank that is supplied to the absorption chiller.

2.3.6 Pipe

Type 31 is used in this simulation. The heat loss coefficient in the pipe is 0.83 W/m^2.K.

2.3.7 Cooling tower

Type 162 is used. The module uses Braun model, with reference in Equation (2) [16].

$$NTU = a\left(\frac{\dot{m}_w}{\dot{m}_a}\right)^n \tag{2}$$

where NTU is the Number of transfer units, a is a parameter with value in a range from 0.5 to 5, n is parameter with value in a range from –0.1 to 0.65, $\dot{m}_w$ is mass flow rate of water, and $\dot{m}_a$ is mass flow rate of air

The values of the parameters used are regressed from data of a cooling tower of the same size from a catalogue of Liangchi Industry (Thailand) Co. Ltd., a manufacturer of cooling tower. The value of the parameter ‘a’ from the Liangchi cooling tower is 1.6076 while that for ‘n’ is 0.1616.

2.4 *Financial performance indicators*

Financial indicators to be used are payback period (PB) and life cycle cost (LCC)

The payback period is the time (number of years) required to recover the cost of an investment. This is calculated from Equation (3)

$$PB = \frac{IC}{\Delta OC} \tag{3}$$

where IC is the differential cost of solar cooling equipment cost over that of conventional system,

ΔOC is the differential annual operating cost between that of conventional system and that of solar cooling system.

The life cycle cost is a method that assess the total discounted cost over a specified period. The life cycle cost, LCC, of a project is calculated from Equation (4)

$$LCC = I + R + E + M \tag{4}$$

where I = investment cost, R = replacement cost, E = energy cost, M = maintenance cost, as sum total of present values or as sum of levelized costs, all discounted to the present.

The applicable electricity tariff is the Time of Use (TOU) tariff. The energy charge is 4.1839 Baht/kWh and the demand charge is 132.93 Baht/kW per month for 22 kV connection, [17]. The maintenance cost per year of solar cooling system is assumed 1%, while for conventional system it is 2.5%, all of initial costs. The discount rate is 7% and electricity escalation rate is 4% as observed in [18].

With a given discount rate i (%) a given cost escalation rate r (%), and a life of n years, the present worth factor, PWF, and the capital recovery factor, CRF, can be calculated from Equation (5)

$$PWF = \left[1 - \frac{(1+r)^n}{(1+i)^n}\right]\left(\frac{1+r}{i-r}\right)$$

$$CRF = \frac{1}{PWF} \tag{5}$$

Table 2 shows the cost of electricity for operation of a 1 kW$_e$ equipment in office and hypermarket operating hours for a year.

Table 2: Cost of electricity (B/Y) for operation of 1 kW$_e$ equipment in office and hypermarket hours

Cost of Electricity (B/Y)	Office	Hypermarket
Energy charge	13,744.1	10,689.9
Demand charge	1,595.2	1,595.2
Total	15,339.3	12,285.0

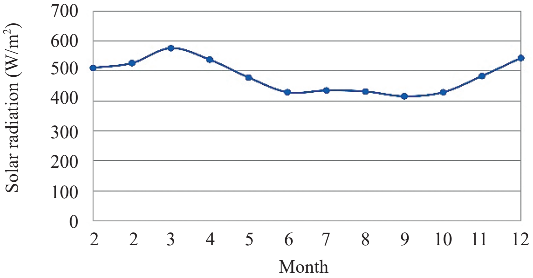

Figure 5: Solar radiation on a 15° inclined plane.

The energy charge is the charge of electrical energy used by the 1 kW$_e$ equipment for the corresponding number of operating hours for each building type from Table 1 and the demand charge if for the contribution to the power demand of the building of each month for the whole year.

3 Results and Discussion

3.1 *Available monthly average solar radiation*

Figure 5 shows monthly average solar irradiance during 8.00 a.m.–5.00 p.m. on the solar collector array that inclines 15° towards south. This angle is similar to the latitude angle of Bangkok and is the same angle for maximum irradiance obtained from a study, [19]. The average solar radiation is 483 W/m^2 and the maximum is 576 W/m^2 that occurs in the month of March. The minimum monthly average is 416 W/m^2 that occurs in the month of September.

3.2 *Sizes of hot water tanks and solar collector array required under the solar autonomous mode*

In order to operate fully in solar autonomous mode, the size of solar collector array and the hot water tank in the minimal configuration in Figure 1 for each type of building must be sufficient so that the solar cooling system meets the load for the required number of hours in Table 1. TRNSYS was run on a trial and error basis by increasing the size of tank and subsequently the size solar collector array to find the number of hours in a year that solar cooling meets the required load. Figure 6 shows results of such trials for office. The figure shows that, for each size of hot water tank, solar operating hours that satisfies the required cooling load increases with increasing size of collector array. With larger tanks, the size of collector array required to reach

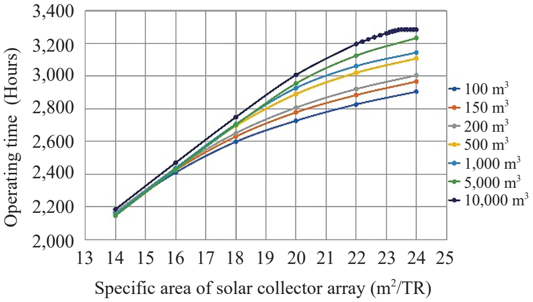

Figure 6: Relationship between operating time of absorption chiller and specific area of collector (Office).

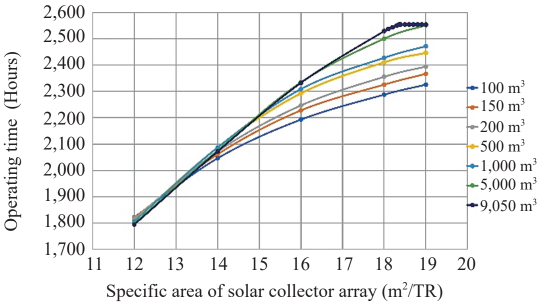

Figure 7: Relationship between operating time of absorption chiller and specific area of collector (Hypermarket).

a given number of hours is smaller. However, collector array smaller than certain size, 16 m^2/TR for the case of office and 14 m^2/TR for hypermarket, the number of solar operating hours seem to be dependent largely on the size of solar collector and independent of tank size. For a tank of 10,000 m^3, the required number of hours, 3,285, in Table 1 is met by using a collector array of 23.5 m^2 per refrigeration ton (TR). The dots in proximity at the upper end in the upper most graph in Figure 6 show the resultant number of hours of solar cooling meets the required load for each incremental increase in the size of collector array. Beyond 23.5 m^2/TR, there is no more increase in the number of hours. Figure 7 shows corresponding graphs for the hypermarket case. Table 3 summarizes the results for both cases for the solar autonomous mode.

Table 3: Sizes of tank and solar collector array required to operate under the solar autonomous mode in each building type

Item	Unit	Office	Hypermarket
Size of tank	m^3	10,000	9,050
Size of solar collector array	m^2/TR	23.5	18.36
	m^2	11,750	9,180

3.3 *Financial viability of solar cooling under the solar autonomous mode*

In order to compare the cost of solar cooling using single-effect absorption chiller fired by hot water heated by solar collector array in the solar autonomous mode in comparison to the cost of electric cooling, basic cost figures of the main components must first be consolidated. The costs of main components of both system are presented in Table 4.

A local company offers a tank of 10 m^3 (diameter 1.72 m and length 4.5 m) for 288,000 Baht and a tank of 15 m^3 (diameter 2 m and length 4.5 m) for 385,000 B. This information is used to derive costs of larger tanks under the following assumptions. The quotations for the tanks are assumed to comprise 4 components: cost

Table 4: Costs of main components of electric cooling and solar cooling systems

System Component	Rated Power, kW$_e$	Cost (B)	Life, years	Capital Recovery Factor
Electric Chiller, 500 TR	310	6,250,000	15	0.109794625
Cooling tower and water pumps, 500 TR	15	435,000	20	0.094392926
Solar collector, per m^2		5,000	30	0.080586404
for office, 11,750 m^2		58,750,000	30	0.080586404
for hypermarket, 9,180 m^2		45,900,000	30	0.080586404
Hot water tank, for office 10,000 m^3		36,195,200	15	0.109794625
for hypermarket, 9,050 m^3		33,325,500	15	0.109794625
Absorption chiller, 500 TR or 1,760 kW$_{th}$	14	6,500,000	50	0.07245985
Cooling tower and water pump, 4,400 kW$_{th}$	40	1,062,000	20	0.094392926

Note: The information on electric and absorption chiller is obtained from LG Corporation, cooling tower from Liangchi Industry (Thailand) Co. Ltd., solar collector from a local vendor. Exchange rate of 33 B to one USD is used to convert all costs in USD to Baths. The escalation rate for the items in Table 4 is assumed zero.

of steel plate and insulation that form the tank body, cost of surface coating and labor, cost of supporting structure that is proportionate to the volume of the tank, and marketing cost. The first two items should be proportionate to the surface area of the tank. The last item would be large for a small tank and small for a large tank.

The tanks are assumed of simple cylindrical shape of length L and diameter D, the surface area and volume of such cylinder can be calculated from Equation (6)

$$\text{Volume} = (\frac{\pi D^2}{4})L,$$

$$\text{Surface area} = D(\frac{D}{2} + L) \quad (6)$$

A local vendor gave quotations of 2,510 B/m^2 for steel plate coded ss400 with a thickness of 12 mm, and 220 B/m^2 for 50 mm rockwool insulation. So that total cost of the first item is 2,730 B/m^2. The tanks are not subject to high pressure and the 12 mm steel plate should suffice for a tank of any size. The second item is assumed equal to that of the first item. For a tank of 10 m^3 and length of 4.5 m, Equation (4) can be used to calculate the diameter of the tank, which gives 1.68 m. The surface area is then calculated from (4) as 28.2 m^2. For this tank, the costs of the first and second item are identical at 77,052 B and summed to 154,104 B. Assuming a marketing cost of 40% of the quoted value or 115,200 B. This leaves the third cost item as 18,695 B. Since this third item is proportionate to the volume of the tank, the cost of this third item is then 1,869 B/m^3. Using the same procedure of calculation for the 15 m^3 tank, the cost of the third item is 2,372 B/m^3. These last two figures are averaged, and the result used as the cost of the third item for calculation of the costs of larger tanks. For the 75 m^3 tank, the marketing cost is 30%. The marketing cost becomes smaller for larger tanks. Table 5 shows results of calculation of the costs for tanks of 75, 125, 1,000, 9,050, and 10,000 m^3, based on the four cost items described. The length of each tank is chosen so that it is roughly 2.5 times its diameter. Tanks of 75 and 125 m^3 are needed in electric chiller-assisted mode and their costs are given here for reference while the cost of 1,000 m^3 tank is listed for comparison.

3.3.1 Comparative costs of the solar autonomous mode and electric cooling mode

Table 6 shows comparative costs of the all-electric cooling and solar autonomous cooling. The initial costs of main equipment of each mode of cooling are given in Table 4, and Table 6 shows the levelized (annualized) cost of each item for the life of each respective item and at 7% discount rate. The abbreviation CT and pumps stands for cooling tower and condenser water pumps. The annual operating costs of both modes are also shown. The annual maintenance cost of electric cooling is 2.5% and of solar cooling is 1% of the respective equipment cost. The operating costs of equipment include the costs of electricity per kW$_e$ in Table 2 multiplied by kW$_e$ rating of each item in Table 4. Table 6 also shows the 50-Y present worth of equipment cost, PW(50,7%), operating PW(50,7%,4%), 4% escalation, and payback periods of solar cooling for both office and hypermarket cases.

The life cycle costs (LCCs) of solar cooling are higher and the payback periods are long for both office, 29 years, and hypermarket, 30 years, cases. The solar autonomous mode is not cost-effective for both types of building.

Table 5: Dimensions and costs of tanks of different sizes

Tank Volume, m^3	**10**	**15**	**75**	**125**	**1,000**	**9,050**	**10,000**
Length, L, m	4.5	4.5	9	10	20	40	40
Diameter, D, m	1.68	2.06	3.26	3.99	7.98	16.97	17.84
Surface area, m^2	28.2	35.8	108.8	150.3	601.3	2585.3	2742.0
Cost item 1&2, B	154,105	195,419	593,863	820,810	3,283,238	14,115,982	14,971,301
Cost item 3, B	18,695	35,581	159,057	265,096	2,120,764	19,192,919	21,207,645
Total cost, B	288,000	385,000	798,095	1,124,998	5,428,321	33,325,463	36,195,226

Table 6: Comparative levelized and 50-Y present worth costs of electric and solar cooling

Electric Cooling			Solar Autonomous Cooling		
Cost Component	**Levelized Cost (B)**		**Cost Component**	**Levelized Cost (B)**	
	Office	**Hypermarket**		**Office**	**Hypermarket**
Equipment			Equipment		
Electric Chiller	686,216	686,216	Solar collector	4,734,451	3,698,916
CT and pumps	41,061	41,061	Hot water tank	3,974,041	3,658,957
			Absorption chiller	470,989	470,989
			CT and pumps	100,245	100,245
Total	727,277	727,277	Total	9,279,727	7,929,107
PW(50,7%)	10,036,970	10,036,970	PW(50,7%)	128,067,155	109,427,592
Operating			**Operating**		
Maintenance	167,125	167,125	Maintenance	1,025,072	867,875
Electric Chiller	4,755,174	3,808,358	Abs Chiller	214,750	171,990
CT and pumps	230,089	184,275	CT and pumps	613,571	491,401
Total	5,152,388	4,159,758	Total	1,853,393	1,531,266
PW(50,7%,4%)	135,523,918	109,414,638	PW(50,7%,4%)	48,750,028	40,277,081
LCC	145,560,888	119,451,608	LCC	176,817,183	149,704,674
			PB (years)	29	30

3.4 *Financial viability of solar cooling under the electric chiller-assisted mode*

The sizes of tanks and solar collector array for each building type to operate under solar autonomous mode and the corresponding equipment and operating costs seem to be very large. If the size of solar array and hot water tank can be reduced to some extent under the electric chiller-assisted mode, it could be more cost-effective. The graphs in Figures 6 and 7 show that for each tank size, reducing the size of collector array, thus reducing its cost, decreases solar cooling time but increases electric chiller operating time, and thus increasing the cost of electricity in the electric chiller-assisted mode. Starting from a relatively small tank size of 100 m^3 and a small collector array of 14 m^2/TR, the graph in Figure 6, for the case of office, implies that the incremental increase in solar cooling time is steep and thus the reduction of electric cooling time is also steep. However, the increase in solar cooling time declines when the size of solar collector increases beyond 16 m^2/TR. This phenomenon implies that the life cycle of the electric chiller-assisted mode could have a concave curve with respect to the size of collector array (for a fixed size of hot water tank). Pursuing along this line and using the life cycle calculation procedure illustrated in Table 6, Figure 8 shows graphs of LCC of application of electric chiller-assisted mode to the office building. Each graph pertains to a tank size and exhibits a concave pattern as observed above. However, the graph for the tank of 125 m^3 shows the lowest LCC with the collector array of 16 m^2/TR. With such configuration, the number of solar cooling hours is 2,421, meaning that the remaining 864 hours are served by electric cooling. Figure 9 shows similar graphs for the case of hypermarket. The lowest LCC is attained at the tank size of 75 m^3 and collector array of 12.5 m^2/TR to achieve 1,884 solar cooling hours and leaving 671 hours of electric cooling.

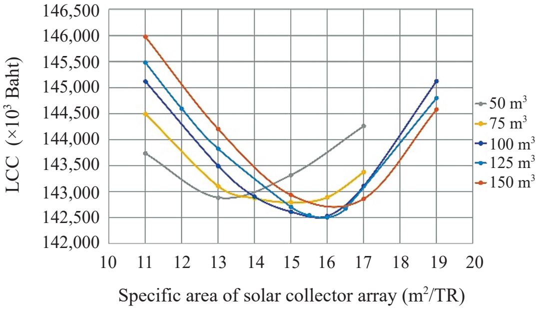

Figure 8: Relationship between LCC of solar cooling system and specific area of collectors under various sizing of hot water tank (Office).

Using the reference information on initial costs and electric power requirements of solar and electric cooling system components in Tables 4 and 5, Table 7 shows initial costs, levelized initial costs, annual operating costs, present worth of 50 years life cycle

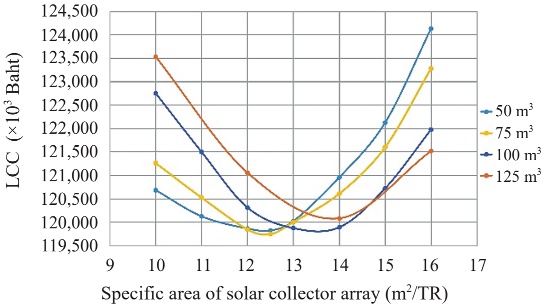

Figure 9: Relationship between LCC of solar cooling system and specific area of collectors under various sizing of hot water tank (Hypermarket).

of operation and payback periods under the electric chiller-assisted solar cooling mode for both office and hypermarket models. The present worth of 50 years of the equipment cost includes a discount of 7%, while that for operating cost also account for escalation in maintenance and energy costs of 4%.

Even though auxiliary heat source is used in reference [11] instead of employment of an electric chiller here, there is certain similarity in the results obtained here, that an optimum tank size, and an optimum collector size are obtained that yields minimum life cycle cost for each building model.

The initial costs for solar cooling under this mode are high while the operating costs are moderate for both office and hypermarket models. The main items for both types of buildings are solar collectors that contribute 60 to over 70% of total equipment costs even when both solar and electric chillers are accounted. In this mode of operation, the sizes of the hot water tanks for both building types are moderate and their cost contributions are also moderate.

Comparing the cost figures in Table 7 to those in Table 6, the most prominent feature is that the LCCs of the electric chiller-assisted mode for both types of building are lower than those of electric cooling and solar autonomous cooling modes. Even though total

Table 7: Minimum costs under the electric chiller-assisted mode for the two building models

Cost Component	Office		Hypermarket	
	Initial, B	Levelized, B	Initial, B	Levelized, B
Equipment				
Electric Chiller	6,250,000	686,216	6,250,000	686,216
CT and pumps	Shares with those of absorption chiller			
Solar collector	40,000,000	3,223,456	31,250,000	2,518,325
Hot water tank	1,124,998	123,519	798,095	87,627
Absorption chiller	6,500,000	470,989	6,500,000	470,989
CT and pump	1,062,000	100,245	1,062,000	100,245
Total	54,936,998	4,604,426	45,860,095	3,863,402
PW(50,7%)		64,111,180		53,317,836
Operating				
Solar cooling hours		2,421		1,884
Maintenance		643,120		552,351
Absorption chiller		164,141		132,687
CT and pumps		468,975		379,105
Electric chiller		1,615,115		1,364,793
CT and pumps		78,151		66,038
Total		2,969,503		2,494,974
PW(50,7%,4%)		78,107,205		65,625,612
LCC		141,651,713		118,943,448
Higher solar initial cost		48,251,998		39,175,095
Lower solar operating cost		2,182,886		1,664,784
PB (years)		22		24

Note: The size of cooling tower and condenser water pumps for the absorption cooling system is about twice that of the electric cooling system and the two systems do not operate simultaneously. The cooling tower and condenser water pumps of the solar cooling system can be designed to comprise two units, one unit serves electric cooling, and both units operated together to serve solar cooling. This arrangement saves costs of equipment for cooling of condenser water of electric chiller.

equipment cost for this mode is higher than that of the electric cooling, it is lower than that of the solar autonomous mode, and its total operating cost is also between the total operating costs of the other two modes. Nevertheless, compare to electric cooling, payback periods of electric chiller-assisted mode are 22 and 24 years for office and hypermarket respectively. These figures are considered long for the typical life cycle of electric chillers.

In Thailand, the Ministry of Energy has operated schemes for promotion of energy efficient equipment that draws financial support from the Energy Conservation Promotion Fund to subsidize replacement of aged equipment or machinery with new and more efficient equipment, [20]. Such schemes could be extended to promoting solar cooling. Promotion of solar cooling is already included in the Alternative Energy Development Plan of Thailand, [4]. A scheme proposed in this paper is to provide subsidy of 30% of the cost of acquisition and installation of solar cooling equipment, here includes solar collector, hot water tank, absorption chiller, and cooling tower and condenser water pumps. Table 8 exhibits financial figures of the results in subsidizing such equipment.

The subsidy reduces the costs of the four equipment items in row 2 to row 6, solar collectors to CT and water pumps by 30%. The overall initial equipment costs by around 25%. The LCCs are reduced by 15% and the payback periods for the solar cooling under the electric chiller-assisted mode, are reduced to 14 and 16 years.

3.5 *Hourly temperature profiles of hot water in the hot water tank*

Office building, Figure 10 exhibits hourly temperature profiles of hot water in the hot water tank under both the solar autonomous mode and the electric chiller-assisted mode for the office building.

With the operation in the solar autonomous mode, the tank and solar collector panel are sized so that the solar chiller is able to operate at all daytime operating duration in Table 1. The water temperature in the tank exceeds 70°C in all operating hours In electric

Table 8: Minimum costs under the electric chiller-assisted mode for the two building models with 30% subsidy on solar cooling equipment

Cost Component	Office		Hypermarket	
	Initial, B	**Levelized, B**	**Initial, B**	**Levelized, B**
Equipment				
Electric Chiller	6,250,000	686,216	6,250,000	686,216
CT and pumps	Shares with those of absorption chiller			
Solar collector	28,000,000	2,256,419	21,875,000	1,762,828
Hot water tank	787,498	86,463	558,667	61,339
Absorption chiller	4,550,000	329,692	4,550,000	329,692
CT and pump	743,400	70,172	743,400	70,172
Total	40,330,898	3,428,963	33,977,067	2,910,247
PW(50,7%)		47,322,246		40,163,575
Operating				
Solar cooling hours		2,421		1,884
Maintenance		497,059		433,521
Absorption chiller		164,141		132,687
CT and pumps		468,975		379,105
Electric chiller		1,615,115		1,364,793
CT and pumps		78,151		66,038
Total		2,823,442		2,376,144
PW(50,7%,4%)		74,265,344		62,500,004
LCC		121,587,590		102,663,578
Higher solar initial cost		33,645,898		27,292,067
Lower solar operating cost		2,328,947		1,664,784
PB (years)		14		16

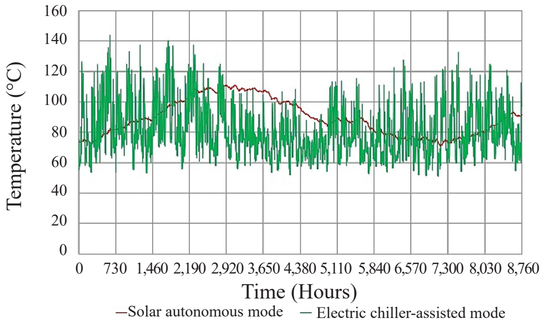

Figure 10: Hot water temperature profile in hot water tank in the solar autonomous and electric chiller-assisted modes for the office building.

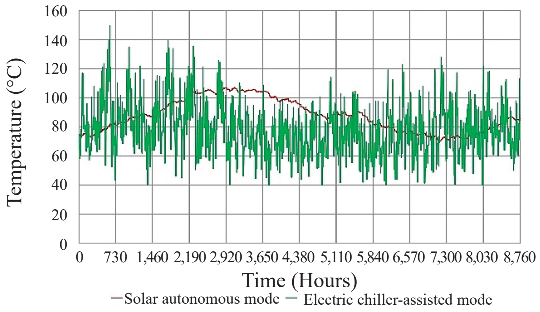

Figure 11: Hot water temperature profile in hot water tank in the solar autonomous and electric chiller-assisted modes for the hypermarket building.

chiller-assisted mode, the number of hours absorption chiller fails to operate is the number of hours the water temperature drops below 70°C.

Hypermarket building, Figure 11 exhibits hourly temperature profiles of hot water in the hot water tank under both the solar autonomous mode and the electric chiller-assisted mode for the hypermarket building.

4 Conclusions

This paper illustrates that solar autonomous cooling requires large solar collector array and large hot water storage and is not cost-effective. It is also physically complicated to build even for a system of moderate cooling capacity.

In Thailand, there are small to medium-size (up to 300 TR) solar cooling installations, but all are based on designs that requires supplementary heating system to raise temperature of hot water used to fire the absorption chiller. So far as is known, most systems are not designed to operate as the sole or main cooling system.

This paper presents results of a simulation study on an alternative solar cooling design based on the use of an electric chiller to supplement the operation of a single-stage absorption chiller. The configuration and the system requirements are deemed practical. It is assumed the system is designed to serve a low-rise office in one case and a hypermarket in another case. The resultant 'cost optimum' system requires a moderate-sized hot water tank, but large solar collector array. The cost of the solar collector array contributes up to 70% of total equipment cost. The paper illustrates that if the cost of solar equipment is subsidized, the overall cost could be reduced to render such system sufficiently attractive.

There is a relative recent demonstration of an alternative absorption chiller based on a so-called 'variable stage' absorption cycle, [21]. The chiller offers higher energy efficiency with a coefficient of performance of up to 1.15 but requires hot water of temperature of 110°C. It is a challenge to develop a solar cooling system using such chiller for application in Thailand as the Thai sky is mainly partly cloudy and the technology for concentrating solar radiation from such sky needs to be developed.

References

[1] Energy Planing and Policy. (2015). Oil and electric usage situation. EPPO. Bangkok, Thailand. [Online]. Available: http://www.eppo.go.th/index.php/th/energy-information/situation-oil-electric?orders[publishUp]=publishUp&issearch=1&start=12

[2] S. Chirarattananon, *Building for Energy Efficiency*. Bangkok, Thailand: Asian Institute of Technology, 2005.

[3] Department of Alternative Energy Development and Efficiency. (2007). Solar Radiation Maps of Thailand. DEDE. Bangkok, Thailand. [Online]. Available: http://www2.dede.go.th/dede/renew/sola/mapmenu.html

[4] Energy Planing and Policy. (2016). Alternative Energy Development Plan. EPPO. Bangkok, Thailand. [Online]. Available: http://www.eppo.go.th/index.php/en/ policy-and-plan/en-tieb/tieb-aedp

[5] T. S. Ge, R. Z. Wang, Z. Y. Xu, Q. W. Pan, S. Du, X. M. Chen, and J. F. Chen, “Solar heating and cooling: Present and future development,” *Renewable Energy*, vol. 126, pp. 1126–1140, 2018.

[6] A. Pongtornkulpanich, S. Thepa, M. Amornkitbamrung, and C. Butcher, “Experience with fully operational solar-driven 10-ton LiBr/H_2O single-effect absorption cooling system in Thailand,” *Renewable Energy*, vol. 33, no. 5, pp. 943–949, 2008.

[7] M. Balghouthi, M. H. Chahbani, and A. Guizani, “Feasibility of solar absorption air conditioning in Tunisia,” *Building and Environment*, vol. 43, no. 9, pp. 1459–1470, 2008.

[8] F. Calise, A. Palombo, and L. Vanoli, “Maximization of primary energy savings of solar heating and cooling systems by transient simulations and computer design of experiments,” *Applied Energy*, vol. 87, no. 2, pp. 524–540, 2010.

[9] F. Agyenim, I. Knight, and M. Rhodes, “Design and experimental testing of the performance of an outdoor LiBr/H_2O solar thermal absorption cooling system with a cold store,” *Solar Energy*, vol. 84, no. 5, pp. 735–744, 2010.

[10] Y. Ma, S. Saha, W. Miller, and L. Guan, “Comparison of different solar-assisted air conditioning systems for Australian office buildings,” *Energies*, vol. 10, no. 10, pp. 1463-1–1463-7, 2017.

[11] E. Bellos and C. Tzivanidis, “Energetic and financial analysis of solar cooling systems with single effect absorption chiller in various climates,” *Applied Thermal Engineering*, vol. 126, pp. 809–821, 2017.

[12] Apogee Interactive. (1993). Compare - Installed Costs – Chillers. Apogee Interactive. Wilmington, US. [Online]. Available: http://c03.apogee.net/contentplayer/?coursetype=ces&utilityid=northwestern&id=1084

[13] University of Wisconsin, “TRNSYS 18: A transient system simulation program,” University of Wisconsin, Madison, USA, 2014.

[14] J. A. Duffie and W. A. Beckman, *Solar Engineering of Thermal Processes*, 4nd ed. New Jersey: John Wiley & Sons, 2003, pp. 67.

[15] ECOTHERM. (2011). Product Specifications and Design Guide. ECOTHERM. Austria. [Online]. Available: http://www.ecotherm.com/upload/files/ Produkte/ESC-V6-V12-V18.pdf

[16] J. E. Braun, “Methodologies for the design and control of chilled water systems,” Ph.D. dissertation, Department of Mechanical Engineering, Faculty of Engineering, University of Wisconsin, Madison, USA, 1988.

[17] Metropolitan Electricity Authority. (2018, Nov.). Large General Service. MEA. Bangkok, Thailand. [Online]. Available: https://www.mea.or.th/en/profile/109/114

[18] P. Sirasoontorn, “Electricity tariff regulation in thailand: Analyses and applications of incentive regulation,” in *Infrastructure Regulation: What Works, Why and How Do We Know?*. Singapore: World Scientific, 2011, pp. 153–188.

[19] N. Saeneerattanaprayune, J. Taweekun, C. Kooptarnond, and P. Ngamsritragul, “A study on efficiency of solar collector for hot water generation using energyplus program,” in *Proceedings of the Conference of Mechanical Engineering Network of Thailand*, 1891, pp. 1282–1287.

[20] Energy Policy and Planning Office. (2016). Thailand Energy Efficiency Development Plan. EPPO. Bangkok, Thailand. [Online]. Available: http://www.eppo.go.th/index. php/en/policy-and-plan/en-tieb/tieb-eep

[21] Z. Y. Xu, R. Z. Wang, and H. B. Wang, “Experimental evaluation of a variable effect LiBr–water absorption chiller designed for high-efficient solar cooling system,” *International Journal of Refrigeration*, vol. 59, pp. 135–143, 2015.