(Invited Paper)

A Study on Energy Performance, Environmental Impacts and Economic Analysis including External Cost of a Solar Water HeaterHaving Heat Pump as an Auxiliary

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Manuscript received February 3, 2014
Revised February 13, 2014

ABSTRACT

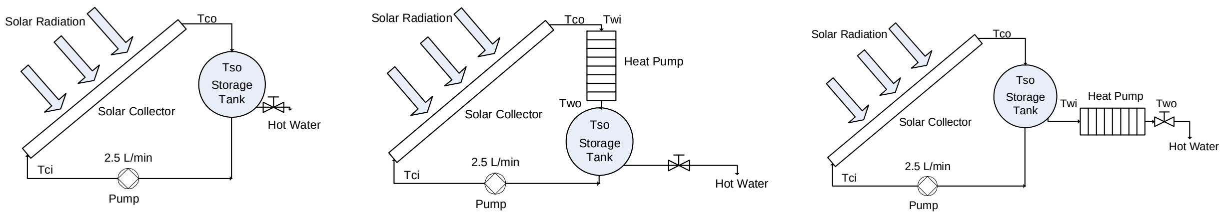
A solar water heater with heat pump as an auxiliary (SWHHP) was investigated in terms of system energy efficiency, environmental impacts and economic costs including global warming externality evaluation. The information data were compared with those of a conventional electric heater (EH) and a common solar water heater with electrical heater as an auxiliary (SWHEH). A profile of hot water consumption during a day was selected from a children nursery office in Chiang Mai, Thailand of which the average daily amount of hot water at 50°C was about 610 liters. In term of system energy efficiency, the SWHHP consumed less electricity consumption significantly compared to the EH and the SWHEH. For environmental impact aspect in term of global warming, the life cycle assessment (LCA) was applied to evaluate the impacts due to their raw material and conventional energy consumptions during the system operation over the entire life of 10 years. It was found that in each unit, the main impact came from electricity consumption of the system operation. The SWHHP was also the best system that gave the lowest environmental impact. For economic analyses, the SWHHP showed the SPP of 3.94 years and IRR of 21.80 % at the optimum area of 4 m^2. When the environmental impact was considered, the SWHHP could reduce CO_2 around 75.04% and 66.45% compared with the EH and the SWHEH, respectively. The SWHHP also gave the best solution when the external cost was included.

Keywords: *Solar water heater, Heat pump, Life cycle assessment, External cost.*

1. INTRODUCTION

In this study, a vapor compression heat pump was used as an auxiliary unit of a solar hot water system instead of an electrical heater due to its lower total power consumption which was around one-third of the latter case. When the hot water temperature in the storage tank was less than the set value, the heat pump absorbed heat from the surrounding ambient at the heat pump evaporator then the heat was upgraded and transferred through the heat pump condenser to the hot water in the storage tank.

Very few studies on auxiliary heat pump in solar water heating system have been reported. Charoenjit et al. (2005) presented different designs in integrating vapor compression heat pump in solar hot water system as shown in Fig. 1. The heat pump was used to generate heat to hot water after solar collector or after the storage tank when the water temperature was less than the set value to keep the outlet temperature leaving the storage tank be steady. The experiments were carried out to generate hot water at around 50 – 60˚C. The power consumption was around 1/2 - 1/3 of that for the common solar water heating unit having an auxiliary electrical heater.



a. General solar water heating system.

b. Solar water heating with heat pump after solar collector.

c. Solar water heating with heat pump after storage tank.

Fig. 1 *Solar water heating with integration of assisted heat pump [Charoenjit et al. (2005)].*

Burapa et al. (2008) reported a solar water heater having a condensing coil of a vapor compression air source heat pump dipped in a storage tank as a heat auxiliary. As the water temperature in the storage tank increased, the overall coefficient of performance, COP, of the heat pump decreased. When the hot water temperature was at 55 ^{o}C, the COP was still over 2 which meant that the power consumption was less than 50% of that from the electrical heater.

In term of environmental impact, Ardente et al. (2005) used a technique of life cycle assessment for a solar collector for sanitary warm water. The system boundary covered production processes, installation, maintenance, disposal and transportation. The functional unit was a solar water heating system which consisted of absorbing collector, water tank and support structure for the roof fastening. The result showed that the input material for manufacturing was about 70-80% of the total environmental impacts. Recently, Purohit and Michaelowa (2008) evaluated clean development mechanism or CDM potential of SWH systems in India. In conclusion, the SWH systems could be of interest since the system could directly reduce greenhouse gas significantly.

This study aimed to consider a solar water heater with an auxiliary heat pump (SWHHP) in three issues which were (1) system energy performance (2) environmental impact and (3) economic analysis including external cost. The results were compared with a conventional electric water heating system (EH) and a solar water heater with an auxiliary electric heater (SWHEH). The hot water consumption profile for the study came from a nursery office in Chiang Mai University Hospital, Chiang Mai Thailand. The appropriate size of solar collectors for the SWHHP was also evaluated when the external cost was included.

2. SOLAR HOT WATER HEATING SYSTEMS

Fig. 2 showed a load profile of hot water in a nursery office in Chiang Mai. High amount of the hot water consumption was in the early morning, in the afternoon and the late afternoon. The required hot water temperature was around 50^{o}C.

Three water heating systems were considered. They were a 3,000 W electric heater (EH), a solar water heater with an auxiliary electric heater (SWHEH) and a solar water heater having an auxiliary heat pump (SWHHP). All the systems had the same water storage tank having a water capacity of 180 liters. Fig. 3 showed the schematic sketch of the SWHHP. The unit consisted of two flat-plate solar collectors each of 2 m^2 in parallel connection. The collectors were south-facing with 18° tilting angle from horizontal plane. At the storage tank, there was a condensing helical coil of a R134a heat pump dipping in the water tank. The heat pump absorbed heat from the surrounding ambient at its evaporator and generated auxiliary heat at the condenser when the water temperature did not reach the set value. The compressor needed an input of 380 W_e. In consideration, it was assumed that utilized hot water temperature was at 50 ^{o}C.

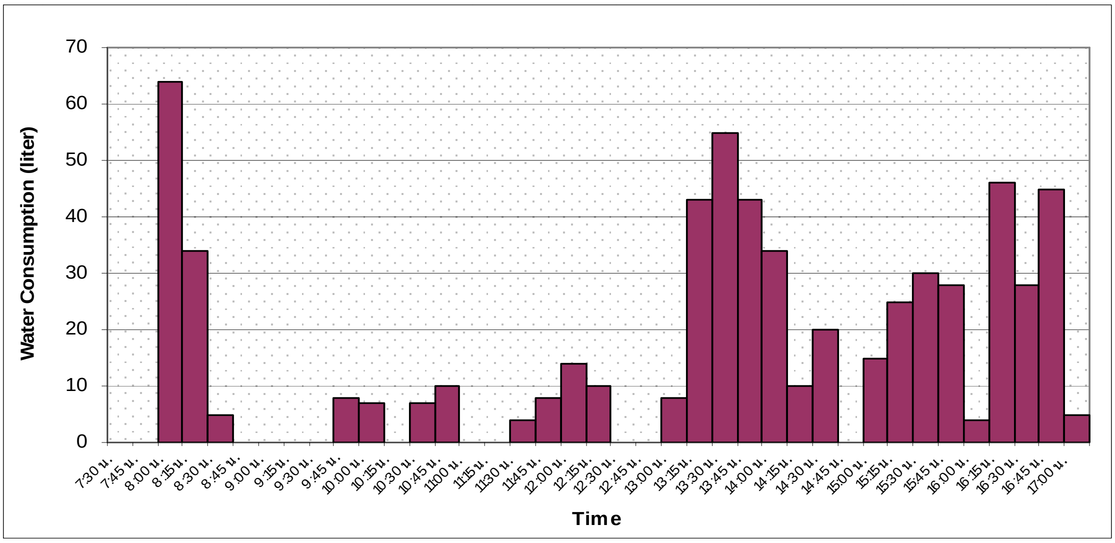


***Fig. 2** Profiles of average hot water consumption during a day of the selected building. The required hot water temperature is 50°C.*

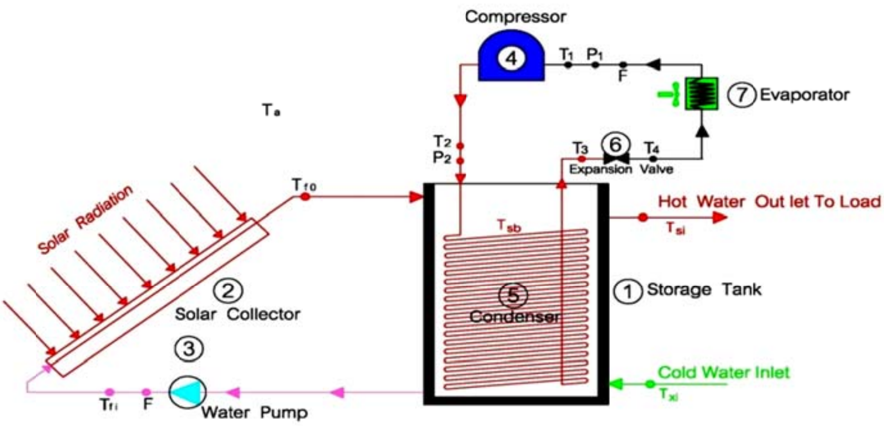


***Fig. 3** Solar water heating system with auxiliary heat pump (SWHHP).*

2.1 Performance Analysis of SWHHP

The solar collector was used to transform solar energy to be thermal energy absorbed by the working fluid inside. The rate of heat gain from the collector could be calculated by

$$\dot{Q}_{coll} = F_R(\tau\alpha)_e I_T A_c - F_R U_L A_c (T_{fi} - T_a). \qquad (1)$$

Q_{coll} was rate of heat gain from solar collector (W); $F_R(\tau\alpha)_e$ and $F_R U_L$ were optical and heat loss characteristics of solar collector, in this study, the values were 0.8 and 10.4 W/m^2 °C, respectively; I_T was solar incidence on solar collector per unit collector area (W/m^2); A_c was solar collector aperture area (m^2); T_{fi} and T_a were temperatures of collector fluid inlet (°C) and of the surrounding ambient (°C), respectively.

T_{fi} could be assumed to be the same as the water in the storage tank T_{sb} then

$$\dot{Q}_{coll} = F_R(\tau\alpha)_e I_T A_c - F_R U_L A_c (T_{sb} - T_a). \qquad (2)$$

To simplify the calculation, the temperature T_{sb} was assumed to be uniform throughout the tank then the energy balance equation should be

$$(M_w C_p)_T \left(\frac{dT_{sb}}{dT} \right) = (\dot{Q}_{coll} + \dot{Q}_{cond} - \dot{Q}_{load} - \dot{Q}_{loss}) \quad (3)$$

M_w was amount of water in the storage tank (kg), C_p was specific heat of water (J/kg ^{o}C), $\dot{Q}_{loss}$ was rate of heat loss from the storage tank (W) and $\dot{Q}_{cond}$ was heat transfer rate from heat pump condenser.

$\dot{Q}_{load}$ was useful heat rate from water storage tank which could be calculated from

$$\dot{Q}_{load} = \dot{m}_L C_p (T_{si} - T_{xi}). \quad (4)$$

$\dot{m}_L$ was useful water mass flow rate(kg/s), T_{si} and T_{xi} were water temperatures (^{o}C) leaving and entering storage tank, respectively. T_{si} could be assumed to be the same value as T_{sb} .

The heat rate at the condenser could be estimated from

$$\dot{Q}_{cond} = \dot{m}_R (\Delta h). \quad (5)$$

$\dot{m}_R$ was refrigerant mass flow rate of heat pump (kg/s), Δh was enthalpy change of refrigerant at condenser (J/kg).

The heat rate at the condenser could also be calculated from energy efficiency ratio, EER, of the heat pump by

$$EER = \dot{Q}_{cond} / P_{power} . \quad (6)$$

P_{power} was total electrical power consumed by the heat pump. The power was on when the value T_{sb} was less than the set point.

The heat pump EER normally varies with the difference between the water temperature in the storage tank and that of the ambient temperature. It could be found to be in a form of

$$EER = a + b\,(T_s - T_a). \quad (7)$$

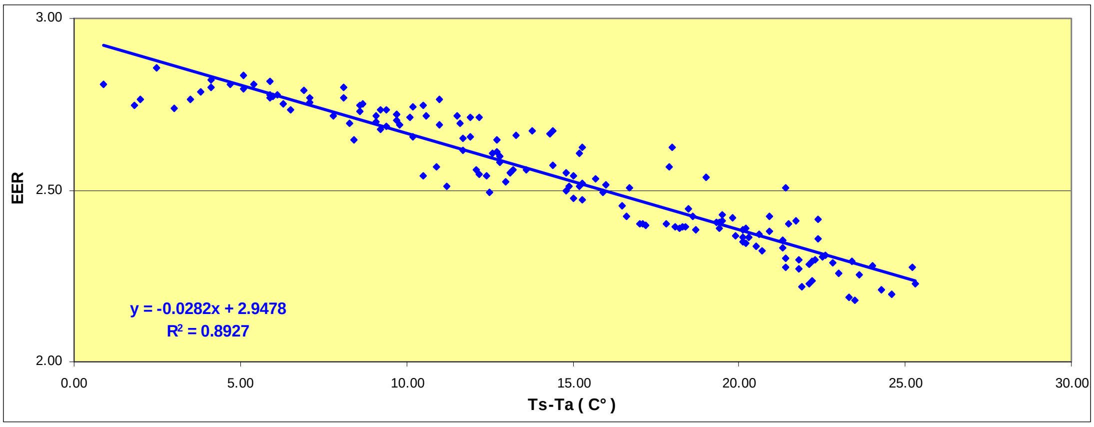


Fig. 4 *A relationship of the heat pump EER with the temperature difference between the water temperature in the storage tank and the ambient temperature.*

Fig. 4 showed the relationship of the heat pump *EER* with the temperature difference $(T_s\text{-}T_a)$ of the tested unit. The values *a* and *b* were 2.9478 and -0.0282 in this study.

Then the heat rate at the condenser could be estimated as

$$\dot{Q}_{cond} = [a + b\,(T_s - T_a)]P_{power}. \quad (8)$$

Equation (3) could be rewritten in numerical form and when the heat loss is neglected then the temperature of the storage tank after the time step Δt could be

$$T_{sb}^{+} = T_{sb} + \frac{\Delta t}{(M_w C_p)_T}[(F_R(\tau\alpha)_e I_T A_c - F_R U_L A_c (T_{sb} - T_a)]$$

$$+[a + b(T_{sb} - T_a)P_{power}] - [m_L C_p (T_{sb} - T_{xi})] \quad (9)$$

For electrical heater (EH) system, $\dot{Q}_{coll}$ in eq. (3) was the heat rate supplied by a 3,000 W electrical heater and $\dot{Q}_{cond}$ became zero. For solar water heating system with an electrical heater as auxiliary, $\dot{Q}_{cond}$ was the heat rate supplied by a 3,000 W electrical heater.

The calculation step for calculating the water temperature at the storage tank was given in Fig. 5.

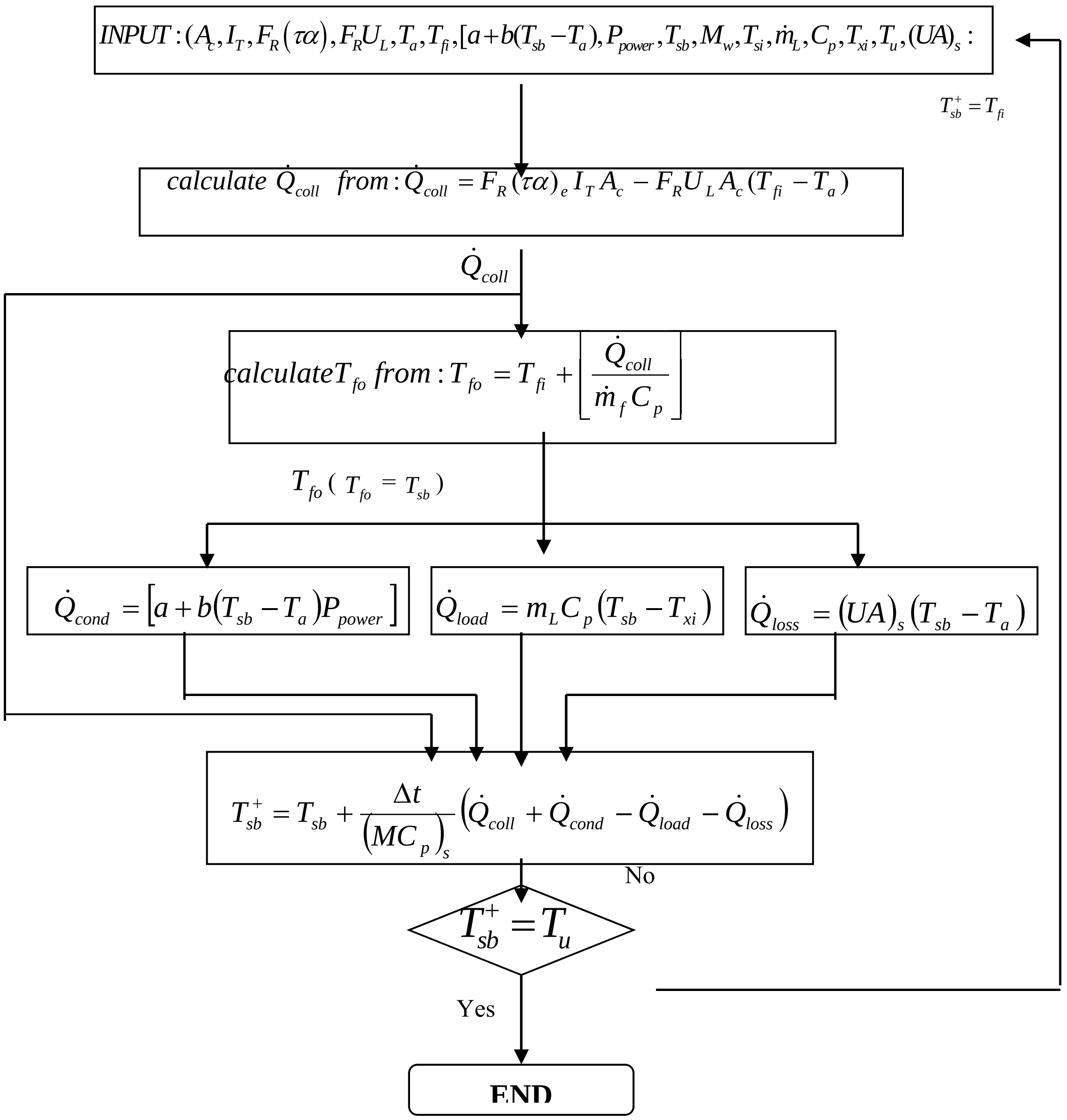


Fig. 5 *The calculation step of the solar water heating system with auxiliary heat pump.*

Fig. 5 showed the calculation step when the solar collector area, the storage tank capacity, the ambient temperature and the system power supply were given, the temperature of water in the tank and that of the utilized hot water at any time could be calculated.

In the system test, there were some important parameters to be measured and recorded which were the temperatures entering and exiting the solar collector, hot water temperature in the tank and the refrigerant temperatures entering and exiting condenser and compressor. Thermocouple type K with a precision of ± 0.1 °C was used for temperature measurements. A rotameter with a range of 0-10 kg/s ± 0.05 kg/s was used for water flow rate measurement in the collector and refrigerant flow rate. Pressure of the refrigerant was directly measured by using a gage with a range of 0-150 psi and 0-250 psi ±1 psi. A multimeter was used for power supply measurement at the compressor and the evaporator fan.

Fig. 6 showed the simulated results compared to the experimental data of the SWHHP system. It was found that the results from the simulation agreed well with the results from the experiment.

The model as described before was then used to calculate the electrical power consumed by each system. Fig. 7 showed monthly electricity consumption of the three water heating systems. It was obviously shown that electricity consumption of the SWHHP system was reduced significantly when compared to those of the EH system and the SWHEH system. The solar radiation data on the collector plane and the ambient temperature as shown in the Appendix were taken.

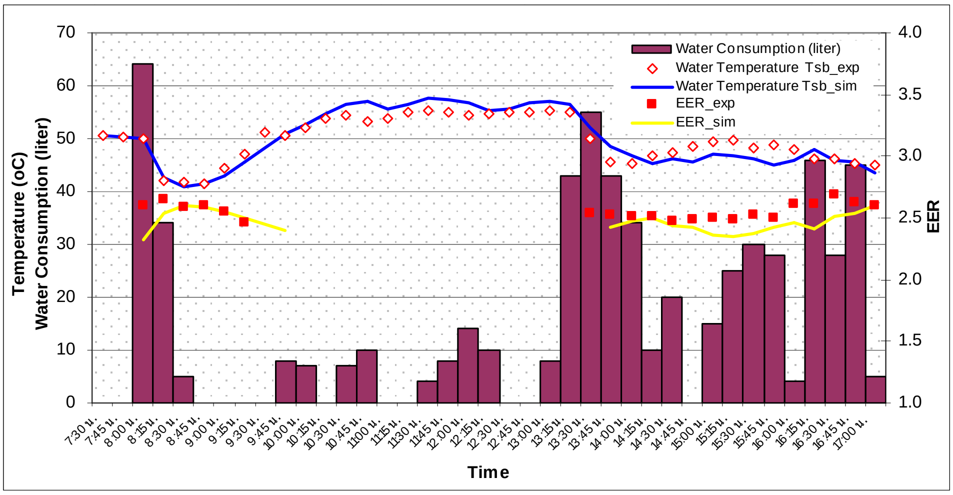


Fig. 6 *Simulated and experimental results of the SWHHP system.*

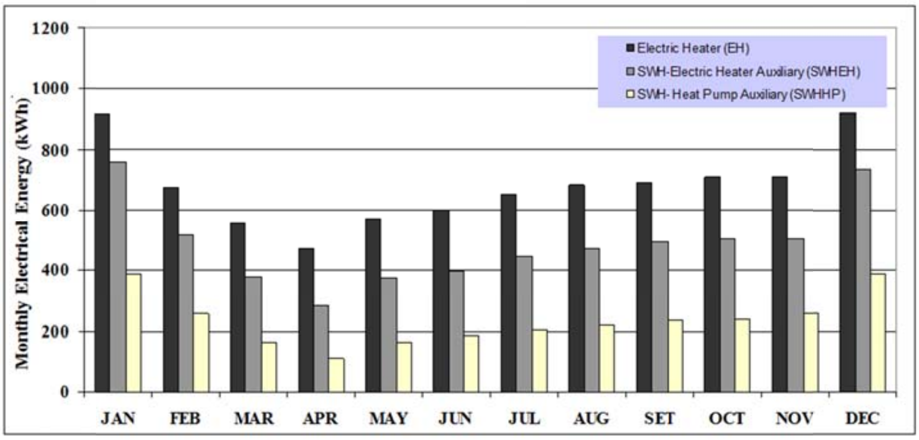


Fig. 7 *Simulation results of electricity consumption results of the three water heating systems.*

2.2 Environmental Impact Evaluation

Life cycle assessment (LCA) was applied to evaluate the environmental impacts of the systems. It was a concept and a methodology to evaluate the environmental effects of a product or activity holistically by analyzing the entire life cycle of a particular product, process, or activity. There were four steps in LCA procedure and for our study they were as follows:

Step 1: Goal and Scope Definitions

The overall goal of this LCA study was to analyze the numerical results of the water heating systems and to compare their results for indicating the best environmental friendly system. The system boundary covered manufacturing phase and operation phase of the systems. Functional unit was a system which was divided into (1) the electric heater system (EH), (2) the solar water heating system with auxiliary electric heater (SWHEH) and (3) the solar water heating system with auxiliary heat pump (SWHHP) system.

Step 2: Life Cycle Inventory (LCI)

The inventory analysis was to map out the environmental interventions which were general terms for emissions and all other inputs and outputs from and to the environment. The primary and secondary data of the energy and the resources inputs and the emission outputs from each phase were collected. The details of each phase data collection were as follows:

(1) Manufacturing Phase

Manufacturing of each system was focused on raw material production and energy consumption in the system production. In this study, inventory of the solar water heating system based on the LCA of the solar thermal collector in Italy (Ardente, et. al., 2005). Inventory of the heat pump and the electric heater materials were primary data or site-specific data.

(2) Operation Phase

The system operation was focused on electricity consumption. The input and output inventory for electricity generation in Thailand was considered. Key assumption of the system was lifespan of 10 years.

Step 3: Life Cycle Impact Assessment (LCIA)

LCIA in this study was based on SimaPro software version 7.1. SimaPro was a software for environmental impact analysis which was specifically developed for life cycle assessment (LCA) by PRe′ consultants, the Netherlands. SimaPro contained a number of inventory databases and impact assessment methods which were used to calculate environmental impact results. The basic structures were:

1. Characterization
2. Damage assessment
3. Normalization
4. Weighting

The last three steps were optional according to the ISO standards. In characterization, the substances that contribute to an impact category were multiplied with a characterization factor that expresses the relative contribution of the substance. The characterization in this study focused only on global warming category. The Global Warming Potential (GWP) analyses were based on Intergovernmental Panel on Climate Change (IPCC) method which was an international framework for climate change evaluation.

Step 4: Life Cycle Improvement Analysis

The aim of this step was to identify potential obstructions in the life-cycle and possibly define improvements to overcome these difficulties. The results of the environmental impact assessment could be a decision-making tool and indicated the method or materials to achieve the best eco-product or eco-process.

2.3 Environmental Impact Analysis

LCI result of the solar water heating system was shown in Table 1. Table 2 and Table 3 showed the LCI of the auxiliary heating system which were heat pump and electric heater, respectively.

Table 1 *Inventory data of input material of the solar collector (1 module, area 2 m^2) and the storage tank 180 liter.*

Material	Amount	Unit
Solar Collector		
- Galvanized Steel	112.6	kg/system
- Copper	13.6	kg/system
- Glass	10.5	kg/system
- Aluminum	4.0	kg/system
- Steel	1.0	kg/system
- HDPE	0.9	kg/system
- LDPE	0.8	kg/system
- Magnesium	0.72	kg/system
Storage Tank		
- Stainless Steel	29.1	kg/system
- Insulator	9.0	kg/system

Table 2 *Inventory data of input material of heat pump.*

Material	Amount	Unit
Stainless Steel	30.14	kg/system
Cast Iron	21.4	kg/system
Copper	3.75	kg/system
Aluminum	14.65	kg/system
Plastics: HDPE	2.25	kg/system
Insulator	4.0	kg/system
Refrigerant Charge	0.4	kg/system

Table 3 *Inventory data of input material of electric heater system.*

Material	Amount	Unit
Braze	0.135	kg/system
Copper	0.137	kg/system
Plastic	0.004	kg/system
Chromium - Nickel	0.004	kg/system
Insulator (Ceramic)	0.073	kg/system

Table 4 showed inventory data of electricity generation in Thailand which was used for evaluating environmental impacts from electricity consumption in the system operation. Table 5 and Fig. 8. showed results of global warming potential from the three systems. In the manufacturing phase the SWHHP system gave the highest environmental impact but in the operation phase, the EH and the SWHEH gave much higher GWP due to higher electricity consumption over the entire life cycle of the systems (10 years).

2.4 Economic Analysis and External Cost

In this study, two methods on economic analysis were considered which were simple payback period and internal rate of return (IRR).

(1) Simple Payback Period (SPP)

SPP analysis was also called payback period analysis. It determined the number of years required to recover an initial investment through project returns. Advantages of the SPP were that it was simple and easily understood. However, time value of money of cost and benefit parameters were not considered. SPP calculation could be

$$SimplePayback\ Period\ (in\ years) = \frac{Initial\ Investment}{Annual\ Saving} \quad (10)$$

(2) Internal Rate of Return (IRR)

IRR was a discount usually used in capital budgeting which made net present value (NPV) of the project cash flow equal to zero. On the other hand, IRR was a discount rate which made NPV of the overall expenses equal to NPV of profits. Relationship between NPV and IRR could be expressed as

$$NPV = \sum_{t=0}^{n} \frac{CF_n}{(1+IRR)^n} = 0 \quad (11)$$

Where NPV was net present value and CF was cash flow generated in a specific period.

Table 4 *Inventory data of electricity generation in Thailand.*

Resource/Energy Input			Product/Emission Output		
Item	**Amount**	**Unit**	**Item**	**Amount**	**Unit**
1. Fuel Oil	0.03981	kg	1. Electricity	1.00	kWh
2. Diesel	0.00269	kg	2. CO	1.60×10^{-4}	kg
3. Natural Gas	0.11143	kg	3. CO_2	7.10×10^{-1}	kg
4. Lignite	0.18205	kg	4. N_2O	2.22×10^{-5}	kg
			5. NO_x	2.27×10^{-6}	kg
			6. NMVOC	3.38×10^{-5}	kg
			7. CH_4	1.48×10^{-5}	kg
			8. Dust	1.20×10^{-4}	kg
			9. SO_2	1.21×10^{-3}	kg
			10. AS	6.87×10^{-9}	kg
			11. Cd	4.10×10^{-10}	kg
			12. Hg	2.00×10^{-11}	kg
			13. Ni	3.89×10^{-9}	kg
			14. Pb	2.20×10^{-8}	kg
			15. V	7.77×10^{-9}	kg
			16. Zn	3.44×10^{-8}	kg

Source: Khamkure (2004)

Table 5 *Global warming potential of the water heating systems.*

System	GWP Manufacturing Phase	GWP Operating Phase	Total GWP	Unit
1. Electric Heater (EH)	243.69	16849.10	17092.79	kg CO_2 - eq
2. SWH - Electric Heater (SWHEH)	561.85	12151.50	12713.35	kg CO_2 - eq
3. SWH - Heat Pump (SWHHP)	952.13	3313.40	4265.53	kg CO_2 - eq

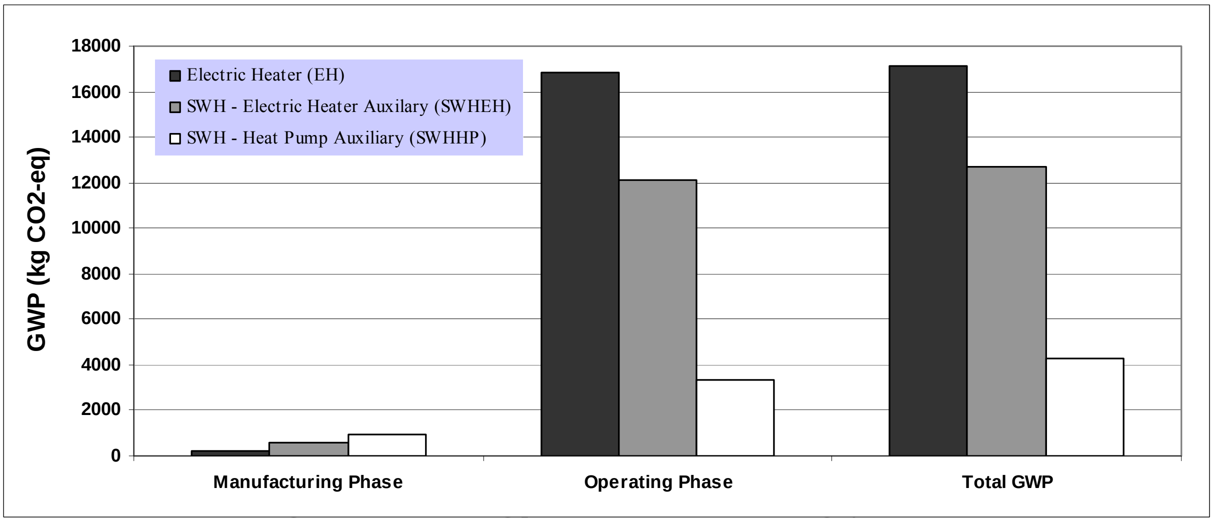


Fig. 8 *Global warming potential of the water heating systems.*

Moreover, externality cost (EC) of the system was also included in this study. Externality was an implicit cost due to the value of environmental damage and it could be estimated from

$$\textit{Externality Cost (EC)} = X_i \times VED_i. \tag{12}$$

Where X_i was the physical amount of the environmental substance *i* ($kg_{pollutant}$/functional unit) and VED_i was value of environmental damage from substance *i* ($cost/kg_{pollutant}$).

In this study, the externality evaluation focused on the environmental damage costs due to global warming potential. The VED estimation was linked to the environmental impact from SimaPro software which was based on equivalency factor (EF) in the characterization step. The EF was a factor to express the substance's strength measured relative to a reference substance. For global warming category, the reference substance was CO_2 and the impact factors thus express the substance's potential impacts as grams of CO_2 equivalent per gram of substance. The VED of substance could be derived as

$$VED_{i,j} = \frac{VED_{base,j} \times EF_{i,j}}{EF_{base,j}} \tag{13}$$

Where $VED_{i,j}$ was value of environmental damage of substance i in impact category j, $VED_{base,j}$ was value of environmental damage of base substance in impact category j, $EF_{i,j}$ was equivalency factor of the substance i in impact category j and $EF_{base,j}$ was environmental impact module of the base substance in impact category *j*. For the global warming damage costs, the VED was based on the average value of climate change damage cost, Australia, (Victoria Transport Policy Institute, 2009) of which the VED of CO_2 was 0.474 US$/kg .

2.5 Economic Analysis and Externality Evaluation

Table 6 showed the economic analytical results of the three water heating systems. For initial cost, the SWHHP showed the highest value while the conventional water heating by electric heater (EH) gave the lowest value. In contrast, the SWHHP showed the lowest electrical energy consumption. For SPP and IRR analyses, the EH was set as a reference for calculating energy saving of the SWHHP and SWHEH systems. It could be seen that SPPs of the SWHHP and the SWHEH were 3.94 years and 10.00 years while IRRs were 21.80% and -0.0022%, respectively. It was also found that the SWHHP offered the lowest total CO_2-eq emission due to its least electrical power consumption over its entire life. The SWHHP and the SWHEH could reduce CO_2-eq over their entire lives around 75.04% and 66.45% of that from the conventional EH system.

Table 6 *Economic analytical results of the water heating systems, (collector area 4 m^2, storage tank 180 liter).*

Item	Conventional Water Heating System: Electric Heater (EH)	Solar Water Heating System		Unit
		Electric Heater Auxiliary (SWHEH)	Heat Pump Auxiliary (SWHHP)	
1. Power Input	3000	3000	380	W
2. Initial Cost	1557	2357	2743	US$
3. O&M Cost (3% of initial cost)	47	71	82	US$/year
4. Lifespan	10	10	10	Years
5. Discount Rate	12	12	12	%
6. Annual Electricity Charge	1000	694	224	US$/year
7. Energy Saving compared with Electric Water Heating	-	306	777	US$/year
8. Simple Payback Period: SPP	-	10.00	3.94	Years
9. Internal Rate of Return: IRR	-	-0.0022	21.80	%
10. GWP entire the life cycle	17092.79	12713.35	4265.53	kg CO_2-eq
11. Externality Cost	8102	6026	2022	US$

2.6 Sensitivity Analysis of the Solar Water Heating System

The mathematical model of the SWH was also used to calculate the auxiliary power when the number of the solar collectors was varied from two modules of 4 m^2 to three modules of 6 m^2 until five modules of 10 m^2 (for 2 m^2 solar collector area, the unit could not maintain the hot water temperature at the existing useful load). The interested parameters, when the collector area was increasing, were the environmental impact increase due to the module production and the environmental impact decrease due to the reduction of electricity in the operation phase. Table 7 showed the sensitivity analytical results of the SWHHP. It could be found that when the number of the collector was increasing the annual electricity consumptions of the system was decreasing and the GWP impacts was less. When focused on economic parameter IRR, the results of the SWHHP were found that the optimum is at 4 m^2 of the solar collector area. Since the increase of energy saving was less than the increase in the investment cost of the solar collector.

Table 7 *Sensitivity analysis of the SWH system with the auxiliary heat pump (SWHHP).*

Number of Module	**2**	**3**	**4**	**5**	**Unit**
Solar Collector Area	4	6	8	10	m^2
Initial Cost	2743	3143	3543	3943	US$
O&M Cost (3% of initial cost)	82	94	106	118	US$/year
Annual Electricity Consumption	224	198	181	168	US$/year
Annual Energy Saving	777	802	819	832	US$/year
GWP - Manufacturing Phase	1271.33	1590.53	1909.73	2228.93	kg CO_2-eq
GWP - Operation Phase	609.74	523.15	469.01	433.43	kg CO_2-eq
GWP entire the life cycle	7368.72	6822.06	6599.83	6563.22	kg CO_2-eq
Externality Cost entire life (EC)	3493	3234	3128	3111	US$
Annual EC (12% discount rate)	199	184	178	177	US$/year
IRR (Excluding EC)	**21.80**	**18.35**	**15.26**	**12.55**	**%**
IRR (Including EC)	**12.51**	**10.56**	**8.28**	**6.03**	**%**

3. CONCLUSIONS

This study attempted to evaluate the water heating systems which it could be concluded as

- Three water heating systems were considered, which were the electric heater water heating system (EH), the solar water heating system with electric heater auxiliary (SWHEH) and the solar water heating system with heat pump auxiliary (SWHHP).
- There were three main issues to be defined which were energy efficiency, environmental impact and economic analysis.
- In energy efficiency issue conclusion, The SWHHP was the best system for energy saving due to its electricity consumption was much lower than the conventional electric heater.
- In the environmental impact analysis, the SWHHP was also the best case due to it offered the lowest global warming potential which was the main impact came from the electricity consumption in the operation phase.
- In economic issue conclusion, the SWHHP was also the best system in which both of general economic consideration and social responsibility externality consideration.
- In final conclusion, the SWHHP was suitable for the water heating system in all three issues which were suitable energy efficiency offered to low environmental impact and economic feasibility.

4. ACKNOWLEDGEMENTS

The authors would like to acknowledge the Commission on Higher Education, Ministry of Education, THAILAND, for the financial support and the Faculty of Medicine, Chiang Mai University for the testing site.

APPENDIX

The solar radiation incidence on the solar collector plane and the ambient temperature of Chiang Mai.

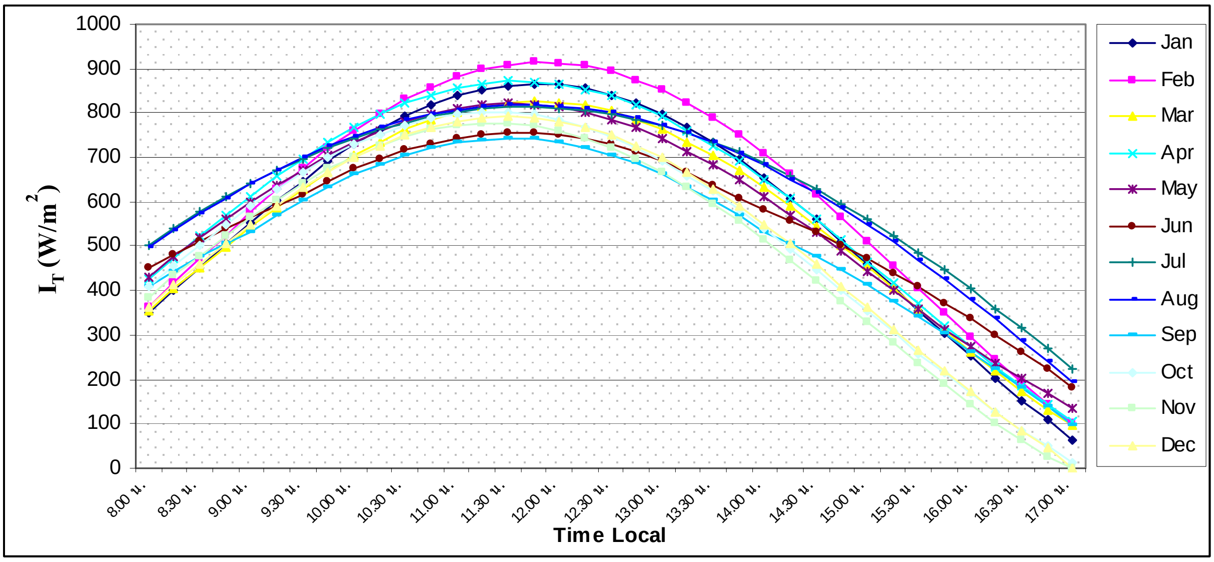


Fig. A1 *The Monthly solar radiation of Chiang Mai.*

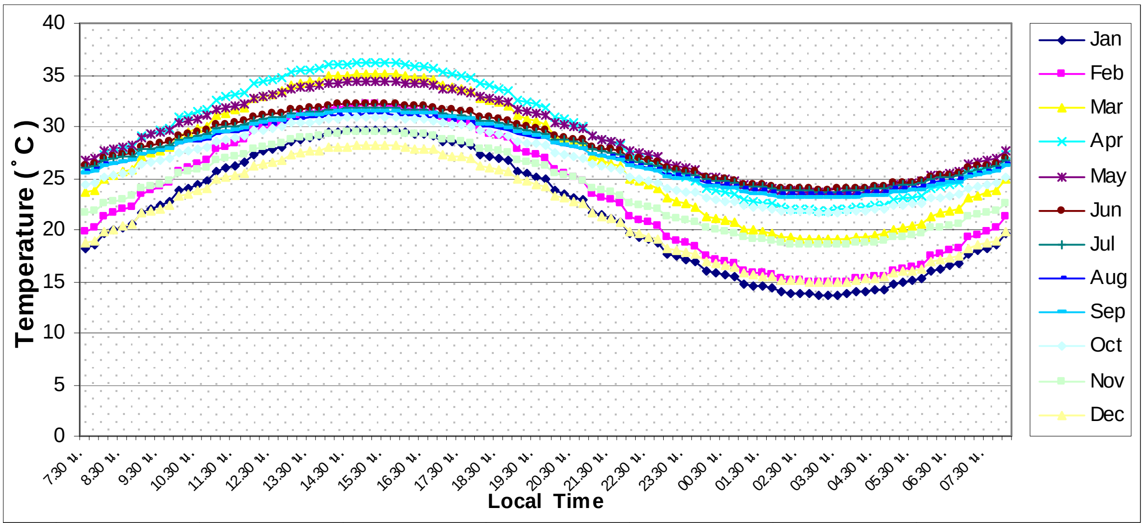


Fig. A2 *The Ambient Temperature of Chiang Mai*

REFERENCES

[1] Charoenjit, C., Tiansuwan, J., Tawarangkura, N., Tia, W. and Kiatsiriroat, T. 2008, Comparison of Solar Water Heating System Performances with Assisted Heat Pump Having R-134a and R-22 as Working Fluids, Proceedings of the 4th Conference on Energy, Heat and Mass Transfer in Thermal Equipments, Chiang Rai, Thailand, pp. 75-82 (in Thai).

[2] Ardente, F., Beccali, G., Cellura, M. and Brano, V. L. 2005, Life Cycle Assessment of a Solar Thermal Collector, Renewable Energy, vol. 30, pp. 1031-1054.

[3] Burapa, M., Vorayos, N., Kiatsiriroat, T. and Chomdee, S. 2008, Simplified Model of Solar Water Heating with Heat Pump Assisted, Industrial Technology , Lampang Rajabhat University, vol. 1 (2), pp. 15-23.

[4] Purohit, P. and Michaelowa, A. 2008, CDM Potential of Solar Water Heating Systems in India, Solar Energy, vol 82, pp. 799-811.

[5] PRe′ consultants, the Netherlands, 2007, SimaPro software version 7.1

[6] Khamkure, S. 2004, An Evaluation of Wastewater Treatment Plant of Electronic Products Using Life Cycle Assessment, Master Thesis of Environmental Engineering, Graduate School Chiang Mai University, Thailand.

[7] Victoria Transport Policy Institute, 2009, Transportation Cost and Benefit Analysis II – Air Pollution **Costs**, [Online], Available for http://www.vtpi.org

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