PHILIPPINE ENGINEERING JOURNAL
PEJ 2013; Vol. 34, No. 2: 60-69

LOCALIZATION AND SAVINGS IN UTILIZATION OF EXTERNAL MELT THERMAL STORAGE SYSTEM FOR AIR-CONDITIONING APPLICATION IN THE PHILIPPINES: A PROOF OF CONCEPT

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ABSTRACT

External melt Thermal Energy Storage (TES) system has a distinct advantage over its conventional water chiller counterpart since it operates and builds up ice during off-peak period when electricity cost is low, and uses the stored coldness during on-peak period when electricity cost is high. This study has proven that TES system can take advantage of this variation in electricity rate, especially when the on-peak electricity cost is very high as in the case of the Philippines. Improvement of system efficiency is also evident given the lower wet bulb temperature of air during night time compared with daytime.

The computation in this study had been based on a recently installed external melt TES utilizing only water and ice, being the first one in the country and installed in a learning institution in Caloocan City, Metro Manila, Philippines. For estimate in savings, ice formation and melting were simulated based on energy analysis conducted every 15 minutes for a period of 24 hours. The computation was also based on industrial time-of-use (TOU) rate of electricity and seasonal ambient air temperature variations in the Philippines over a period of one year. On the thermal side of computation, it assumes steady-state condition and neglects the effect of film coefficient inside the tubes due to nucleate boiling of the refrigerant. It also takes into consideration the combined presence of system cooling demand and compressor cooling capacity.

The total instantaneous cooling demand of the system is about 1,147 kW (326.2 tons of refrigeration, TR). It operates 19-hours a day with compressor resting period from 5 – 9 PM (5 hours) and from 6 –7 AM (1 hour), to ensure continuous chilled water supply even during the hottest time of the day. A partial TES was selected in the design of the installed system considering optimization and balance between energy savings and insufficient allocated space for full TES. The increase in first cost is about US$55,000 which is due to adding TES components as compared to using only components of conventional water chiller. This increase in cost is about 14% of the chiller system and can be recovered in 2.55 years with internal rate of return (IRR) of about 32%. The TES system can yield an annual savings of US$22,000 in electricity, which is about 12% of the chiller power cost. This savings is a combined economic effect of TOU power rate and improvement in the coefficient of performance (COP).

Increasing the ice thickness-on-coil from the conventional 6.35 cm (2.5 in) to 7.24 cm (2.85) by locally fabricating the TES tank reduced the needed additional first cost by about 10% and the floor area of the tank by 11.64% of the floor area necessary for utilizing the standard tank for the conventional TES thickness.

Keywords: *thermal energy storage, external melt, ice, time-of-use rate*

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Received: December 12, 2012
Accepted: April 18, 2013

1. INTRODUCTION

TES systems can refer to a number of technologies that store energy for later use, a scheme that can reduce operating and maintenance costs in central air-conditioning systems. In principle, the external-melt TES builds and stores ice on the external surface of a heat exchanger (normally a coil submerged in a non-pressurized water tank) at night when electricity costs are low and uses that stored coldness to meet the cooling demand the next day when the power costs are high.

In tropical locations where one of the biggest shares in operating expense is contributed by air-conditioning systems [1-3], the choice of cooling equipment is generally dictated by economics, both on operating and first costs. Capitalizing on the price difference between on-peak and off-peak electricity costs, TES can be an attractive alternative to conventional water chiller system [4]. Without a substantial differentiation between the day and night power rates the operational benefits derived from this alternative air-conditioning system may not be cost-effective. As such, a detailed study and system analysis must be done on a case-to-case basis with special attention on the chilled and condenser water pump power consumptions at partial load and night-time power rates. This paper elucidates the projected economic advantages of external-melt TES air-conditioning facility that utilizes ice over conventional water chiller equipment that provides the same cooling output.

This paper had been presented in Sustainable Future Energy 2012 conference [5] and is published in the proceedings of the conference.

2. TES FACILITY USED IN THIS STUDY

The external-melt TES facility is a commissioned library and museum building of a university located in Caloocan City, Metro Manila, Philippines, with a total floor area of approximately 8,000 m^2. Peak, instantaneous cooling demand is 1,147 kW (326.2 TR), with the facility open from 8 AM to 9 PM (13 hours/day). The facility was designed and the TES ice build-up was modeled [6] on the bases of cost and space optimizations and mass and energy balance. It operates 19 hours a day with compressor resting period from 5 – 9 PM (5 hours) and from 6 –7 AM (1 hour) to ensure continuous chilled water supply even during the hottest time of the day. A partial TES was selected in the design of the installed system considering optimization and balance between energy savings and insufficient allocated space for full TES.

The external-melt TES system, with a schematic diagram shown in Figure 1, has direct refrigerant feed designed for maximum ice thickness of 72.4 mm (2.85 in). The chiller of the system is direct expansion, single-stage and water-cooled type, and uses semi-hermetic reciprocating compressors and R-507 refrigerant. Suction temperature used was -10^{0}C based on -6.62^{0}C evaporator temperature and 3.38^{0}C temperature difference between the coil and compressor suction. Compressor discharge temperature used was 40^{0}C for water-cooled application. The evaporator is serpentine type, using 19.05 mm, schedule 40, seamless black iron pipe (ASTM A-53). TES tank material is 6.35 mm-thick mild steel plate with angle bar reinforcement and 100 mm thick, single-sided panelized polystyrene insulation on the walls and 75 mm thick polyurethane block insulation at the bottom. Tank cover is a demountable type, double-sided, 50 mm thick polystyrene panelized insulation.

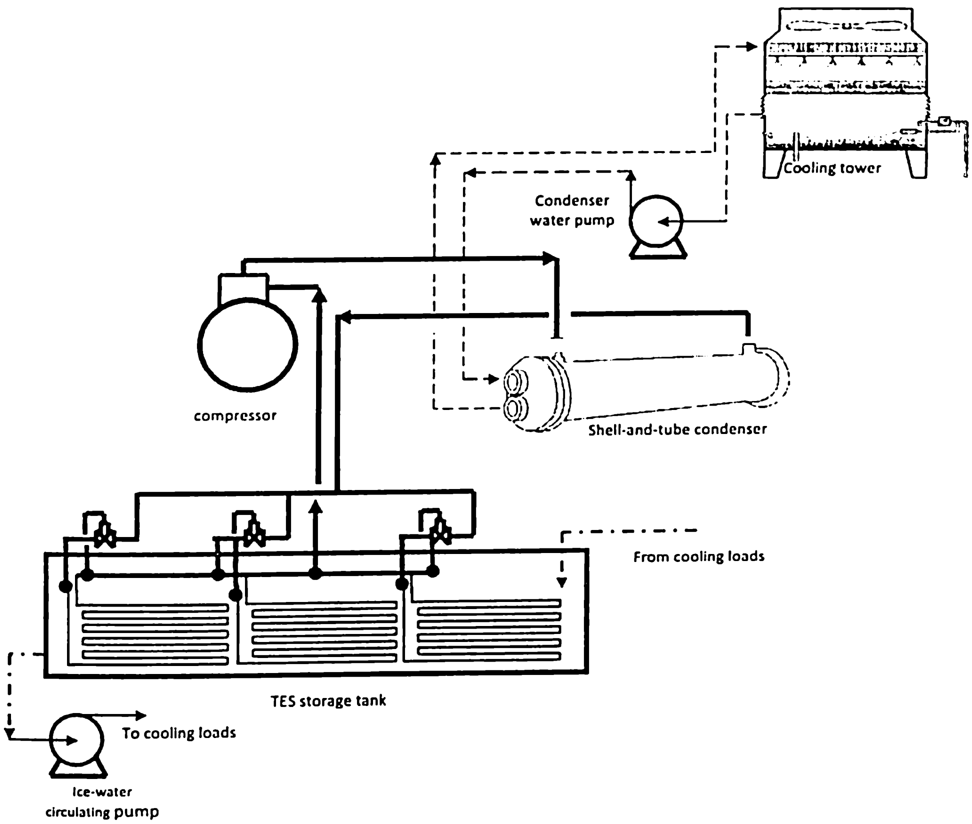

Fig. 1 Schematic diagram of the external-melt TES system.

3. ECONOMIC ADVANTAGE OF THE TES FACILITY

For an estimate in savings, ice formation and melting were simulated based on energy analysis conducted every 15 minutes for a period of 24 hours. On the thermal side of computation, it assumes steady-state condition and neglects the effect of film coefficient inside the tubes due to nucleate boiling of the refrigerant. It also takes into consideration the combined presence of system cooling demand and compressor cooling capacity.

The economic justification in Table 1 shows the cash flow, IRR, difference in investment cost and simple payback computations for TES compared to conventional system. Incoming cash flow for 5 years is the savings in operating cost due to savings using TOU power rate. IRR was computed for 5.54%, 5.854% and 6.19% annual power rate adjustment. Initial increase rate was based on the average inflation rate for the past 8-years (from year 2003 to late September 2009) while the succeeding two years rate were based on compounded rate of the first year [7]. Adopting at least the 5.54% annual power increase rate, the payback period will be 2.55 years with IRR of about 32%. This was the basis for annual cash inflow in the IRR table.

Tables 2 and 3 show list of equipment and operational cost data for water chiller and TES partial storage systems. Variation in compressor power requirement due to seasonal changes in environmental condition was computed on 24-hour cycle. The difference in initial cost (ΔP, in PhP) from Table 1, which is about US$55,000 (USD 1 is approximately PhP 42), was derived from the worksheets of power consumptions of different components in the conventional water chiller and TES systems shown in Tables 4 and 5, respectively.

Table 1.
Economic Justification

	Assumed Power Rate Increase		
	5.54%	5.85%	6.19%
ΔP	-2,325,040.00	-2,325,040.00	-2,325,040.00
year 1	911,533.10	911,533.10	911,533.10
year 2	962,058.07	964,858.60	967,978.19
year 3	1,015,383.58	1,021,303.69	1,027,918.55
year 4	1,071,664.84	1,081,050.88	1,091,570.61
year 5	1,131,065.69	1,144,293.32	1,159,164.21
IRR	31.88%	32.11%	32.37%
payback, yrs	2.5507	2.5507	2.5507

Table 2.
Equipment List (Water chiller option)

ID No.	Equipment	Qty.	System Operating time, hr	Rated motor power input, kW	kW-hr/day
1	York water chillers connected in parallel (model YLFW 160D), each with capacity of 160TR at-13°C evaporating and 40°C condensing temperatures, R-134a refrigerant, with matching shell-and-tube evaporator, shell-and-tube condenser, suction accumulator, oil separator and other standard accessories.	2	13	134.89	3,507.20
2	Bottle-type cooling tower, Liang Chi brand, 1,125.11 kW (320 TR) heat rejection rate at 39°C and 32°C entering and leaving water temperatures and 28°C wet-bulb ambient temperature, with 1 set cooling tower fan @ 10hp motor drive, 230v-3P-60hz power supply.	1	13	11.43	148.61
3	Cooling tower pumps, TACO brand (non-overloading), direct-coupled centrifugal type, pump specification: 480gpm x 80ft TDH x 20hp x 1750rpm, 230v-3P-60hz power supply	2	13	22.86	594.44
4	Chilled water pump, TACO brand (non-overloading), direct-coupled type, pump specification: 384gpm x 140ft TDH x 25hp, 230v-3P-60hz power supply	2	13	28.58	743.05
5	6.35TR fan-coil units, ceiling concealed type, chilled water temperature increase across coil of 15oF, (including chilled water flow control), fan specification: ¾-in wg x 1000 cfm x ¾-hp, 230v – 3P-60hz power supply.	48	13	0.56	349.13
6	3.57 TR fan-coil units, ceiling concealed type, chilled water temperature increase across coil of 15°F, (including chilled water flow control), fan specification: ¾-in wg x 1000 cfm x ½-hp, 230v-3P-60hz power supply.	6	13	0.37	29.09
7	Airconditioning equipment cost, excluding piping, FCU thermostats and chilled water controls, ducting insulation and electrical works	1	**16,306,960**		

Table 3.
Equipment List (TES Partial Storage option)

ID No.	Equipment	Qty	System Operating time, hr	Rated motor power input, KW	kW-hr/day
1	FRASCOLD semi-hemetic reciprocating compressors connected in parallel (3 x W50 168Y), each with capacity of 103.6 kW at 13oC evaporation and 40°C condensing temperatures, R-507 refrigerant, with matching shell-and-tube condenser, suction accumulator, oil separator and other standard accessories for medium temperature refrigeration system	6	19	41.78	4,762.35
2	Bottle-type cooling tower, Liang Chi brand, 1,125.11 kW (320 TR) heat rejection rate at 39°C and 32°C entering and leaving water temperatures and 28°C wet-bulb ambient temperature, with 1 set cooling tower fan @ 20hp motor drive, 230v-3P-60hz power supply.	1	19	7.46	141.74
3	Cooling tower pumps, TACO brand (non-overloading), direct-coupled centrifugal type, pump specification:301gpm x 90ft TDH x 15hp x 1750rpm, 230v-3P-60hz power supply.	2	19	11.19	424.22
4	Chilled water pump, TACO brand (non-overloading), direct-coupled type, pump specification: 312gpm x 100ft TDH x 15hp, 230v-3P-60hz power supply.	2	13	11.32	294.36
5	Air blower, 3hp, 230v-3P-60hz	1	19	2.24	42.52
6	6.35TR fan-coil units, ceiling concealed type, chilled water temperature increase across coil of 15°F, (including chilled water flow control), fan specification: ¾-in wg x 1000 cfm x ¾-hp, 230v – 3P-60hz power supply.	48	13	0.56	349.13
7	3.57 TR fan-coil units, ceiling concealed type, chilled water temperature increase across coil of 15°F, (including chilled water flow control), fan specification: ¾-in wg x 1000 cfm x ½-hp, 230v-3P-60hz power supply.	6	13	0.37	29.09
8	Airconditioning equipment cost, excluding piping, FCU thermostats and chilled water controls, ducting insulation and electrical works	1	**18,632,000**		

Table 4.
Annual Power Requirement (conventional water chiller option).

Time of day	January to June, Php/kW-hr		July to December, Php/kW-hr		Motor power kW	January to June			July to December			Total power cost Php
	Mon - Sat	Sun	Mon - Sat	Sun		operating hrs	kW-hrs	Php	operating hrs	kW-hrs	Php	
1:00 AM	2.3426	2.5022	2.3426	2.3426	0.00	0	0.00	0.00	0	0.00	0.00	0.00
2:00 AM	2.3426	2.3426	2.3426	2.3426	0.00	0	0.00	0.00	0	0.00	0.00	0.00
3:00 AM	2.3426	2.3426	2.3426	2.3426	0.00	0	0.00	0.00	0	0.00	0.00	0.00
4:00 AM	2.3426	2.3426	2.3426	1.8649	0.00	0	0.00	0.00	0	0.00	0.00	0.00
5:00 AM	2.3426	2.3426	2.3426	1.8649	0.00	0	0.00	0.00	0	0.00	0.00	0.00
6:00 AM	2.3426	2.3426	2.3426	1.8649	0.00	0	0.00	0.00	0	0.00	0.00	0.00
7:00 AM	2.3426	2.3426	2.3426	1.8649	384.10	132	50,701.15	118,772.50	132	50,701.15	118,772.50	237,545.01
8:00 AM	2.6256	2.3426	2.5022	2.3426	384.10	132	50,701.15	133,120.93	132	50,701.15	126,864.41	259,985.33
9:00 AM	5.779	2.3426	2.6256	2.3426	384.10	132	50,701.15	293,001.92	132	50,701.15	133,120.93	426,122.85
10:00 AM	6.5283	2.5022	5.9872	2.5022	384.10	132	50,701.15	330,992.29	132	50,701.15	303,557.90	634,550.19
11:00 AM	6.5283	2.5022	6.5283	2.5022	384.10	132	50,701.15	330,992.29	132	50,701.15	330,992.29	661,984.58
12:00 PM	6.5283	2.5022	5.9872	2.5022	384.10	132	50,701.15	330,992.29	132	50,701.15	303,557.90	634,550.19
1:00 PM	6.5283	2.5022	5.9872	2.5022	384.10	132	50,701.15	330,992.29	132	50,701.15	303,557.90	634,550.19
2:00 PM	6.5283	2.5022	6.5283	2.5022	384.10	132	50,701.15	330,992.29	132	50,701.15	330,992.29	661,984.58
3:00 PM	6.5283	2.5022	5.9872	2.5022	384.10	132	50,701.15	330,992.29	132	50,701.15	303,557.90	634,550.19
4:00 PM	6.5283	2.5022	5.779	2.5022	384.10	132	50,701.15	330,992.29	132	50,701.15	293,001.92	623,994.21
5:00 PM	5.9872	2.5022	5.5481	2.5022	384.10	132	50,701.15	303,557.90	132	50,701.15	281,295.03	584,852.92
6:00 PM	5.9872	2.5022	5.9872	2.6456	384.10	132	50,701.15	303,557.90	132	50,701.15	303,557.90	607,115.80
7:00 PM	6.5283	5.779	6.5283	5.5481	384.10	132	50,701.15	330,992.29	132	50,701.15	330,992.29	661,984.58
8:00 PM	6.5283	5.779	5.9872	5.5481	384.10	132	50,701.15	330,992.29	132	50,701.15	303,557.90	634,550.19
9:00 PM	5.9872	3.2594	5.779	2.6256	384.10	0	0.00	0.00	0	0.00	0.00	0.00
10:00 PM	3.2594	2.6294	2.6256	2.5022	0.00	0	0.00	0.00	0	0.00	0.00	0.00
11:00 PM	2.6256	2.5022	2.5022	2.3426	0.00	0	0.00	0.00	0	0.00	0.00	0.00
12:00 AM	2.5022	2.3426	2.3426	2.3426	0.00	0	0.00	0.00	0	0.00	0.00	0.00
						1,848	709,816.04	4,130,941.74	1,848	709,816.04	3,767,379.04	7,898,320.78

Table 5.
Annual Power Requirement (TES partial storage option)

Time of day	January to June, Php/kW-hr		July to December, Php/kW-hr		January to June			July to December			Total power cost Php
	Mon - Sat	Sun	Mon - Sat	Sun	operating hrs	kW-hrs	Php	operating hrs	kW-hrs	Php	
1:00 AM	2.3426	2.5022	2.3426	2.3426	132	75,734.60	177,415.87	132	8,039.03	18,832.23	196,248.10
2:00 AM	2.3426	2.3426	2.3426	2.3426	132	75,734.60	177,415.87	132	8,039.03	18,832.23	196,248.10
3:00 AM	2.3426	2.3426	2.3426	2.3426	132	75,734.60	177,415.87	132	8,039.03	18,832.23	196,248.10
4:00 AM	2.3426	2.3426	2.3426	1.8649	132	75,734.60	177,415.87	132	8,039.03	18,832.23	196,248.10
5:00 AM	2.3426	2.3426	2.3426	1.8649	132	75,734.60	177,415.87	132	8,039.03	18,832.23	196,248.10
6:00 AM	2.3426	2.3426	2.3426	1.8649	132	73,267.46	171,636.36	132	1,383.07	3,239.97	174,876.33
7:00 AM	2.3426	2.3426	2.3426	1.8649	132	73,267.46	171,636.36	132	1,383.07	3,239.97	174,876.33
8:00 AM	2.6256	2.3426	2.5022	2.3426	132	81,520.55	214,040.35	132	9,781.79	24,476.00	238,516.36
9:00 AM	5.779	2.3426	2.6256	2.3426	132	85,042.14	491,458.53	132	10,004.94	26,268.97	517,727.50
10:00 AM	6.5283	2.5022	5.9872	2.5022	132	85,042.14	555,180.61	132	10,004.94	59,901.58	615,082.18
11:00 AM	6.5283	2.5022	6.5283	2.5022	132	85,042.14	555,180.61	132	10,004.94	65,315.25	620,495.86
12:00 PM	6.5283	2.5022	5.9872	2.5022	132	85,042.14	555,180.61	132	10,004.94	59,901.58	615,082.18
1:00 PM	6.5283	2.5022	5.9872	2.5022	132	85,042.14	555,180.61	132	10,004.94	59,901.58	615,082.18
2:00 PM	6.5283	2.5022	6.5283	2.5022	132	85,042.14	555,180.61	132	10,004.94	65,315.25	620,495.86
3:00 PM	6.5283	2.5022	5.9872	2.5022	132	78,306.50	511,208.35	132	10,004.94	59,901.58	571,109.93
4:00 PM	6.5283	2.5022	5.779	2.5022	0	0.00	0.00	0	0.00	0.00	0.00
5:00 PM	5.9872	2.5022	5.5481	2.5022	0	0.00	0.00	0	0.00	0.00	0.00
6:00 PM	5.9872	2.5022	5.9872	2.6456	0	0.00	0.00	0	0.00	0.00	0.00
7:00 PM	6.5283	5.779	6.5283	5.5481	0	0.00	0.00	0	0.00	0.00	0.00
8:00 PM	6.5283	5.779	5.9872	5.5481	0	0.00	0.00	0	0.00	0.00	0.00
9:00 PM	5.9872	3.2594	5.779	2.6256	132	81,211.62	486,230.21	132	10,004.94	57,818.55	544,048.76
10:00 PM	3.2594	2.6294	2.6256	2.5022	132	76,229.87	248,463.63	132	8,527.86	22,390.75	270,854.38
11:00 PM	2.6256	2.5022	2.5022	2.3426	132	75,734.60	198,848.76	132	8,039.03	20,115.26	218,964.02
12:00 AM	2.5022	2.3426	2.3426	2.3426	132	75,734.60	189,503.11	132	8,039.03	18,832.23	208,335.34
					2508.0	1,504,198.50	6,346,008.04	2,508.0	157,388.50	640,779.64	6,986,787.68

Table 6 shows the comparison of power consumption of TES partial storage to conventional water chiller. The values for the annual projected energy consumption of electric motors of the two systems include: compressors, cooling towers, chilled water pumps and cooling tower pumps. These are the equipment most affected by the seasonal and diurnal variation in environmental condition. The fan coil units are almost similar for the three systems; hence, they are not included in the computation.

Annual electricity consumption for water chiller option was computed at 1,419,632 kW-hrs costing PhP 7,898,321, while for TES option, the consumption was 1,661,587 kW-hrs/year costing PhP 6,986,787.68 (Tables 4 and 5). The electricity rates used in the computation are listed in Table 7, which were the prevailing rates before the installation of the TES facility. The cost difference between the two systems is around PhP 911,533 (about US$22,000). Based on projected operating time and total power requirement of the air-conditioning system, the annual average kW/TR consumptions of conventional water chiller and TES partial storage systems are 0.773 and 0.667, respectively. Annual TES electricity savings due to COP improvement alone brought by lower ambient conditions is about 2% of the water chiller annual power cost. The initial cost comparison does not include the electrical and piping requirements of the two systems. It is expected that electrical works are cheaper due to smaller compressor as a consequence of compressor-aided scheme. Chilled water pump motors are also smaller due to lower chilled water flow rates as a result of large chilled temperature difference. Also, piping and insulation sizes are smaller due to lower flow rates, which results to cheaper piping, fittings and insulation costs. Total cost savings amounts to 12% based on projected electricity bill using TOU power rates with breakdown as follows: 14% due to improvement in COP and 86% due to TOU power rates. COP increased because of lower ambient temperature at night, leading to lower condenser temperature of the corresponding chiller of the TES system.

4. CONCLUSIONS

Simulation results show that custom-designed, locally fabricated TES cooling coil, with instantaneous cooling demand of about 1,147 kW (326.2 TR) and maximum ice thickness of 7.24 cm (2.85-in.) will require an increase in initial investment by about 14.26% compared to conventional water chiller of the same capacity. However, its annual projected power consumption will be roughly PhP 911,533 (about 22,000 USD) lower, or about 12% of water chiller power cost which is a combined economic effect of time-of-use (TOU) power rate and improvement in COP. This will result in 31.88% internal rate of return at 5-year cash flow or equal to about 2.55-year simple payback period.

Increasing the ice thickness-on-coil from the conventional 6.35 cm (2.5 in) to 7.24 cm (2.85) made possible by locally fabricating the TES tank in order to minimize the floor area of the tank for ice making in the TES and reduce the costs was also explored. As a result, the needed additional first cost was reduced by about 10% and the floor area of the locally fabricated tank led to 11.64% reduction in floor area necessary for utilizing the standard tank of commercially available models.

Table 6.
Comparison of Operating Parameters and Costs
(Conventional chiller vs. TES partial storage).

Particulars	Conventional Water Chiller (1)	TES partial storage (2)
Annual operating time, hours [A]	3,696	5,016
Total annual power consumption, kW-hrs [B]	1,419,632	1,661,587
Average hourly power consumption, kW [C = B/A]	384	331
Total compressor capacity, TR [D]	497	497
Average annual kW/TR [E = C/D]	0.773	0.667
kW/TR reduction, % [F=(E1- E2) / E1]	Basis of comparison	13.76%

Computation of total savings due to COP improvement and TOU power rate

Particulars	Conventional Water Chiller (1)	TES partial storage (2)
Power cost, PhP/yr [G]	7,898,321	6,986,788
Annual power savings, PhP [H = G1 - G2]	Basis of comparison	911,533
Annual power cost reduction, % [H/G1] x 100%	Basis of comparison	11.54%
Percentage of reduction due to COP improvement [F]	Basis of comparison	13.76%
Percentage of reduction due to TOU power rate [100%-F]		86.24%

Table 7.
Return on Rate Base- Time-of-Use (RORB-TOR) Rates in PhP/kW-hr the Luzon Grid, 16 February 2009 [8].

PERIOD	(JANUARY - JUNE)		(JULY - DECEMBER)	
	Monday - Saturday	Sunday/Holiday	Monday - Saturday	Sunday/Holiday
1:00 AM	2.3426	2.5022	2.3426	2.3426
2:00 AM	2.3426	2.3426	2.3426	2.3426
3:00 AM	2.3426	2.3426	2.3426	2.3426
4:00 AM	2.3426	2.3426	2.3426	1.8649
5:00 AM	2.3426	2.3426	2.3426	1.8649
6:00 AM	2.3426	2.3426	2.3426	1.8649
7:00 AM	2.3426	2.3426	2.3426	1.8649
8:00 AM	2.6256	2.3426	2.5022	2.3426
9:00 AM	5.7790	2.3426	2.6256	2.3426
10:00 AM	6.5283	2.5022	5.9872	2.5022
11:00 AM	6.5283	2.5022	6.5283	2.5022
12:00 AM	6.5283	2.5022	5.9872	2.5022
1:00 PM	6.5283	2.5022	5.9872	2.5022
2:00 PM	6.5283	2.5022	6.5283	2.5022
3:00 PM	6.5283	2.5022	5.9870	2.5022
4:00 PM	6.5283	2.5022	5.7790	2.5022
5:00 PM	5.9872	2.5022	5.5481	2.5022
6:00 PM	5.9872	2.5022	5.9872	2.6256
7:00 PM	6.5283	5.7790	6.5283	5.5481
8:00 PM	6.5283	5.7790	5.9872	5.5481
9:00 PM	5.9872	3.2594	5.7790	2.6256
10:00 PM	3.2594	2.6256	2.6256	2.5022
11:00 PM	2.6256	2.5022	2.5022	2.3426
12:00 PM	2.5022	2.3426	2.3426	2.3426

5. ACKNOWLEDGMENTS

The author would like to thank Dr. Menandro S. Berana of Mechanical Engineering Department, UP Diliman College of Engineering for his comments and inputs on the manuscript. Also, sincere appreciation is given to the Engineering Research and Development for Technology (ERDT) Program of the Department of Science and Technology – Science Education Institute (DOST – SEI) of the Republic of the Philippines for the research dissemination fund.

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