LCM Optimization by Using a Higher-Efficiency Chilled Water Supply System and Implementing Optimal Combinations of Maintenance Methods

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SUMMARY

Energy saving requirements make it imperative to cut CO_2 emissions, reduce energy consumption, and curtail costs at the same time. Life Cycle Management (LCM) evaluations are used to assess the effects of such energy saving efforts. In this study, LCM evaluations were conducted on the air-conditioning chilled water supply system installed as an ESCO facility in the cleanrooms at a semiconductor manufacturing plant. A detailed analysis of the overall system including the pumps, cooling towers, and chillers was conducted to identify the effects of using higher-efficiency absorption chillers and explore optimal mixes of maintenance methods. The analysis yielded quantitative indications of reduced Life Cycle Cost (LCC) and Life Cycle CO_2 ($LCCO_2$) emissions attributed to the use of advanced chillers. The scheme and timing of maintenance practices best suited for specific types of chillers and the degree of cooling water fouling were also identified.

INTRODUCTION

The concepts of LCM that minimize LCC and $LCCO_2$ are becoming permanent parts of modern corporate management. Many existing studies concerning LCM focus on LCA-based environmental evaluation techniques and LCC evaluations. The work done by Actacir[1], Elsafty[2], and others typifies the research conducted on LCC in the chiller air-conditioning sector. These studies are concerned at best with developing comparative evaluations of individual units of equipment, however, and have yet to launch a detailed probe into maintenance-recommended practices.

This study analyzed the effects of using higher-efficiency absorption chillers and explored optimal mixes of maintenance methods from the perspective of LCM evaluations of a chilled water supply system. The following summarizes the major aspects of this study.

- A comprehensive LCM evaluation of the overall chilled water supply system including the pumps, cooling towers, and chillers with regard to the partial load characteristics of the chillers and characteristics of cooling water temperature

- Identification of the optimal methods of maintaining absorption and turbo chillers from the standpoint of optimized LCM, by evaluating how maintenance methods make differences in their effects of energy saving on equipment and in the cost of is equipment.

SUMMARY OF LCM EVALUATION

The chilled water supply system under discussion was installed as an Energy Service Company (ESCO) facility. Because the system is committed to a contractual period of 10 years, both LCC and $LCCO_2$ were evaluated with regard to this period (see Figure 1).

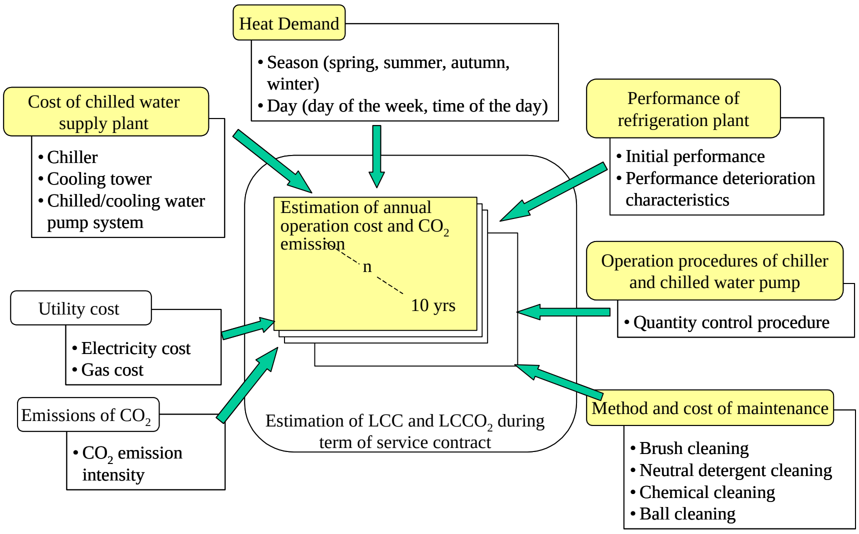


Figure 1. Evaluation system of LCM at refrigeration plant

Estimating LCC

LCC is the sum total of costs for initial equipment installation, operation and maintenance, plus the cost of equipment scrapped. The energy charge is for driving the chillers, cooling towers, and pumps. Annual costs have been evaluated on an NPV (Net Present Value) basis, with an assumed discount rate of 2% per annum.

Estimating $LCCO_2$

The $LCCO_2$ value of a chilled water supply system consisting primarily of chillers is the sum total volume of CO_2 emissions released during system construction and operation, and during the maintenance and scrapping of the chillers.

OUTLINE OF CHILLED WATER SUPPLY-DEMAND SYSTEM

Chilled water supply facility and heat demand

Chilled water is fed to the cleanrooms at the semiconductor manufacturing plant[3]. In the chilled water supply system shown in Figure 2, water is chilled to a temperature of

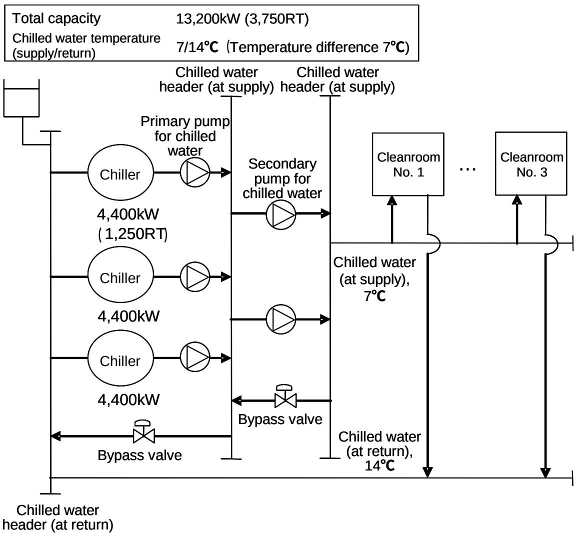
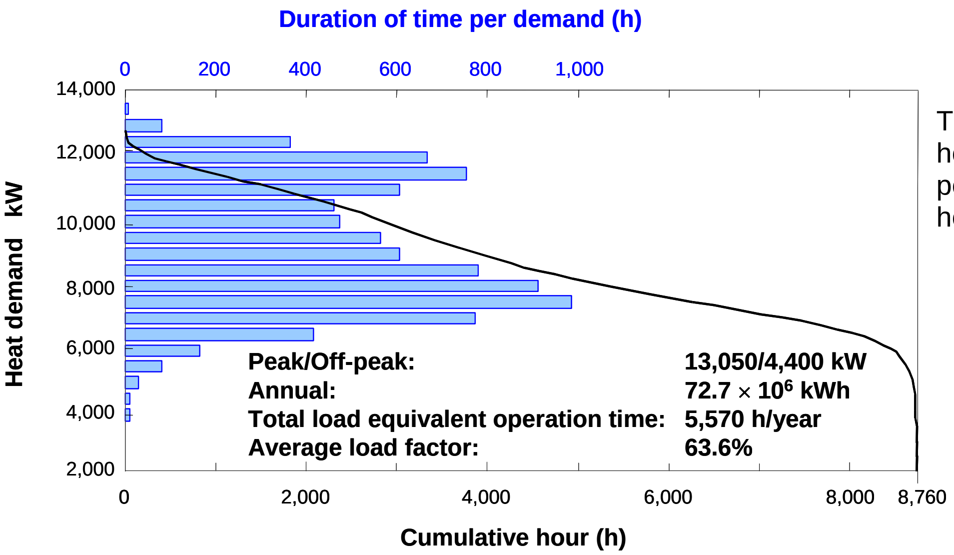


Figure 2. Schematic diagram of chilled water supply system

7°C when supplied and is at 14°C when returned. The maximum and minimum heat demands are 13,050 kW and 4,400 kW, respectively.
Figure 3 shows the heat load demand and annual cumulative time (in hours). The annual demand for heat load is 72.7 x 10^6 kWh. The annual demand for heat load divided by the maximum demand for heat load yields a total-load equipment operation time of 5,570 hours. This plant is running all year-round, with an average load factor as high as 64.5%.



The annual operating hour equivalent to peak load is 5,570 hours.

Figure 3. Head demand and annual cumulative time

Performance of chilled water supply system

(1) Turbo chillers

The turbo chiller model using HFC134a as a refrigerant has two-stage economizer and subcooler to achieve higher efficiency. This model conforms to standard specifications and has chilled-water inlet and outlet temperatures of 12°C and 7°C, respectively.

LCM evaluation requires the use of a database covering performance data on chillers working under wide operating conditions; thus we used a cycle simulator for turbo chiller performance data. The coefficient of performance (COP) was then calculated using a chiller load factor between 20% and the maximum load factor, and a cooling water temperature from 12 to 32°C, with and without using a compressor inverter.

Figure 4 plots the results of a simulation performed with cooling-water temperature settings of 24°C and 16°C, in addition to the rated 32°C.

The maximum output exceeds rated capacity in case of cooling water temperature less than 32°C. This characteristic can make the number of chillers to be run reduced.

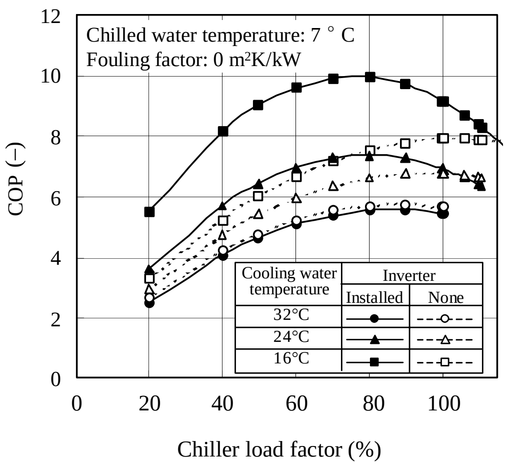


Figure 4. Turbo chiller partial load characteristics

(2) Absorption chillers (steam-driven double-effect/triple-effect)

a. Double-effect absorption chiller

The double-effect chiller (Photo 1) has evaporators and absorbers split into two stages to maintain a heat exchanger temperature difference, and recover heat from condensed refrigerant to achieve a steam consumption rate of 3.5 kg/RT.h and COP value of 1.5 during rated operations.

Photo 1. High efficiency double-effect steam-driven absorption chiller

b. Triple-effect absorption chiller

This study also considered a triple-effect absorption chiller. The first machine, which uses gas directly, achieved a COP value of 1.6 (HHV). We modified performance simulator from gas to steam medium, and an expected steam consumption rate can be 2.81 kg/RT.h and COP value can be 1.87 under rated condition.

Figure 5 shows the partial load characteristics of the double-effect and triple-effect absorption chillers. The COP value of the turbo chiller is converted to primary energy input. The power plant generating efficiency is assumed to be 41.9%.

Chiller performance effect due to fouled cooling water

Fouled cooling water could impair the heat transfer characteristics of the chiller condenser, resulting in degraded chiller performance. Using the cycle simulator, the chiller performance deterioration associated with fouled water has been determined by calculations (see Figure 6).

Changes in chiller performance without cleaning the CD tube have been calculated based on the assumption that the fouling factor would increase by 0.086 m^2K/kW per year and twice.

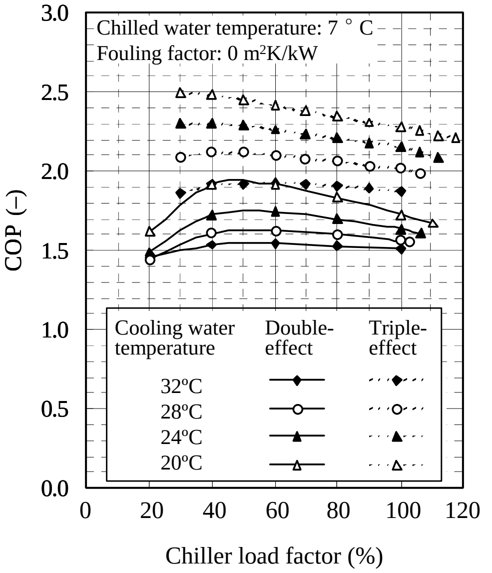


Figure 5. Partial load characteristics of a double-effect absorption chiller (steam consumption rate: 3.5 kg/RT.h) and triple- effect absorption chiller (steam consumption rate: 2.81 kg/RT.h)

The chart reveals quantitative drops in cooling capacity and COP with increases in fouling. The absorption chiller suffers drastic drops in chiller capacity with increased fouling, but its COP only drops slightly.

The deterioration of chilling capacity with the progress of cooling water fouling is more marked on the absorption chiller than the turbo chiller. The rate of reduction in the COP is not much varied among the different chiller types.

Two kinds of cooling water have been selected to be fouled: good and poor. The effect of water fouling upon the condenser was assumed to be 0.86 (m^2K/kW) per year for good-quality water and 1.72 per for poor-quality one.

Cleaning CD tubes and resultant improvements in performance

Brush cleaning (BrC), ball cleaning (BaC), and chemical cleaning (ChC) are typically employed to clean inside the condenser (CD) tubes of turbo chillers. Conversely, cleaning using a natural detergent (NDC) instead of brush or ball cleaning is the preferred method of CD cleaning of absorption chillers.
This study has extended its discussions to include four cleaning methods (see Table 1).

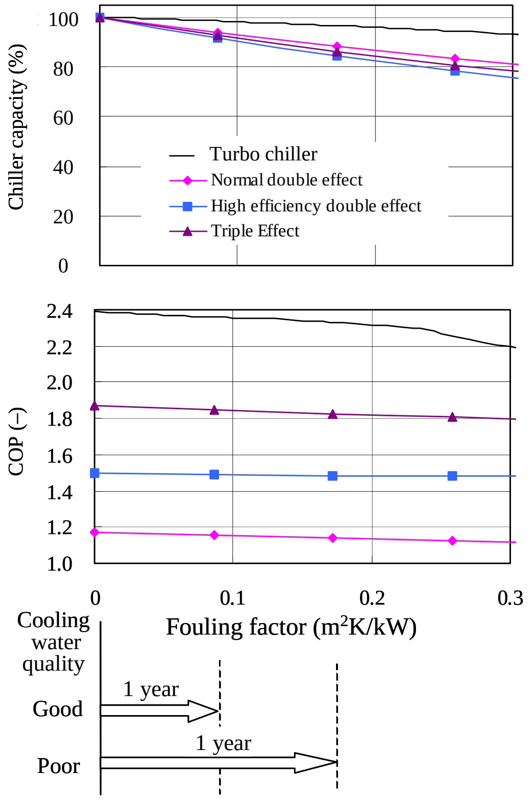


Figure 6. Chiller performance deterioration affected by cooling water fouling

Table 1. Methods of cleaning CD tubes in each chiller and their effects by cleaning methods

Maintenance method	Brush cleaning (BrC)	Neutral detergent cleaning (NDC)	Chemical cleaning (ChC)	Ball cleaning (BaC)
Applied chiller type	Turbo chiller	Absorption chiller	Turbo and absorption chillers	Turbo chiller
Cleaning method	Cleaning inside the CD tubes with a wire brush.	Cleaning inside the CD tubes with a neutral detergent.	Acid-cleaning inside the CD tubes	Inserting spongy balls into the CD tubes to remove contaminants.
Frequency	Once a year	Once a year	Once every several years	Once every several days
Effect (provisional value)	Up to 98% of the COP value obtained one year ago can be recovered.	Up to 98% of the COP value obtained one year ago can be recovered.	The condition of the chiller at initial installation can be restored.	Up to 99% of the COP value obtained one year ago can be recovered.

LCM EVALUATION

Evaluating LCM

1) Method of LCM comparative evaluation

The LCM of three types of chillers has been analyzed over a 10-year period. The following patterns of maintenance were discussed.

- Maintenance is conducted once a year.
- BaC is performed every week.

- At least three years must be allowed to elapse after former ChC practice to minimize the risks of local corrosion on the chiller condenser. (Once ChC is conducted in a given year, no other method of cleaning is employed at the same year.)

2) Method of calculating LCC

The following describes the method of calculating 10-year LCC for the chilled water supply system. The total amount of LCC (or LC) is represented in Eq. (1) as follows:

$$LC = IC + \sum_t \phi_E \bar{E}_E + \sum_t \varphi_E E_E + \sum_t \phi_G \bar{F}_G + DC \qquad (1)$$

where, IC denotes the investment cost, $\bar{E}_E$, the rate of power consumption [Nm^3/year], E_E the contractual demand [kW], $\bar{F}_G$ the gas consumption rate [Nm^3/year], t a 10-year period, ϕ the electric energy charge 7.7 [yen/kWh], φ_E the electric basic charge 1,740 [yen/kW month], and ϕ_E the gas energy charge 35 [yen/Nm^3]. The third term of Eq. (1) is zero for a turbo chiller, because it does not use gas.

3) Method of calculating LCCO$_2$

LCCO$_2$ is determined by summing up the volume of CO$_2$ emissions calculated from the energy emitted over a 10-year period and that of CO$_2$ emissions at the time of chilled water supply system initial manufacturing/installation, and scrapping. The total volume of CO$_2$ emissions of each system is calculated as LE by solving Eq. (2) as follows:

$$LE = E_I + \tau_E \cdot C_E + \tau_G \cdot C_G + E_S \qquad (2)$$

where,
E_I: Volume of CO$_2$ emissions at chiller manufacturing and installation [t-CO$_2$]
τ_E: CO$_2$ emission intensity due to electric power (0.555x10^{-3}) [t-CO$_2$/kWh]
C_E: Total electric power consumption rate [kWh]
τ_G: CO$_2$ emission intensity due to gas (2.097x10^{-3}) [t-CO$_2$/Nm^3]
C_G: Total gas consumption rate [Nm^3]
E_S: Volume of CO$_2$ emissions at equipment scrapping [t-CO$_2$]

Table 2 lists the volumes of CO$_2$ emissions [t-CO$_2$] at system and scrapping.

Table 2. Volumes of CO$_2$ emissions at chiller installation and scrapping

Type of chiller		Volume of CO$_2$ emissions at manufacturing and installation (t-CO$_2$)	Volume of CO$_2$ emissions at scrapping (t-CO$_2$)	Total volume of CO$_2$ emissions
Turbo chiller		564	60	624
Absorption chiller	Double-effect	345	40	385
	Triple-effect	414	50	464

4) Costs of chillers and maintenance equipment/procedures

Table 3 lists different types of chillers and maintenance equipment (BaC) and the costs incurred to maintain them by chiller condenser cleaning method. The triple-effect absorption chiller supply facility requires the cost of equipment, 1.8 times higher than turbo chillers. Among the four cleaning methods, ChC is most costly.

Table 3. Costs of chillers and their maintenance

Model / Item		Turbo chiller	Absorption chiller			
			Double-effect (COP)			Triple-effect (COP 1.87)
			1.17	1.3	1.5	
Equipment and installation cost (million yen)	Chilled water supply facility (system as a whole)	375	453	466	488	675
	Maintenance equipment (BaC, common use)	+10	-			-
Maintenance cost (million yen/time/system)	BrC	1.5	-			-
	NDC	-	1.8	1.8	1.8	2.4
	BaC	2.4	-			-
	ChC	6.0	6.0	6.0	6.0	6.9

Evaluating the effects of LCM by chiller type and cooling water quality

The LCM values of each chiller associated with differences in water quality were evaluated. Absorption chillers optimize their LCM when serviced by annual NDC, coupled with ChC conducted at four-year intervals, and turbo chillers optimize their LCM when serviced by BaC, coupled with ChC conducted at four-year intervals.

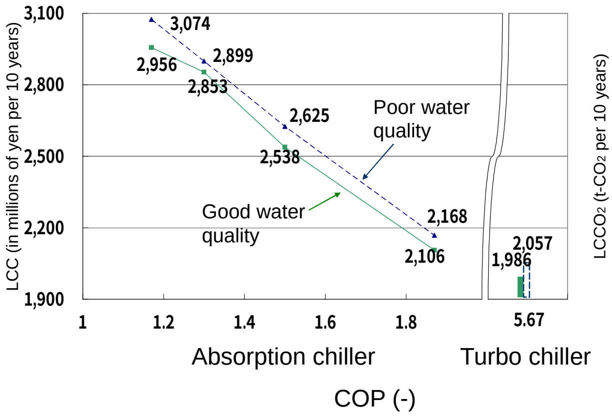


Figure 8. Evaluated effects of LCC by chiller's type

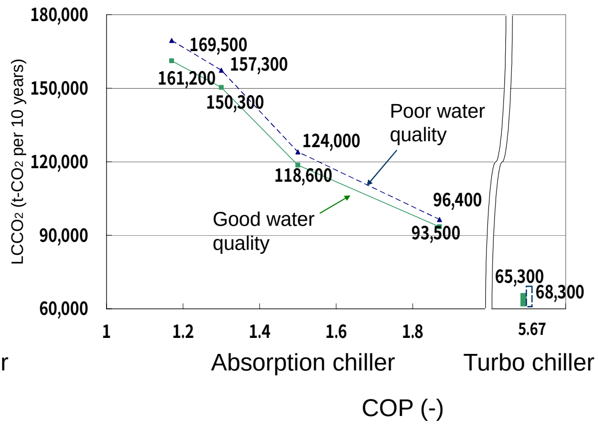


Figure 9 Evaluated effects of $LCCO_2$ by chiller's type

As shown in Figure 8, absorption chillers can reduce their LCC with increases in the COP. Turbo chillers are more cost-effective than absorption chillers. As long as the water is good, the difference between a triple-effect absorption chiller and a turbo chiller remains at about 120 million yen. If the water quality worsens, however, the difference would escalate by 11 million yen. Hence, turbo chillers are more affected by water quality than triple-effect absorption chillers.

As can be seen in Figure 9, turbo chillers are superior to absorption chillers in terms of $LCCO_2$. $LCCO_2$ affected by water quality is almost same as triple-effect and turbo chiller.

Figure 10 shows the relation between LCC and $LCCO_2$ in terms of maintenance and water quality. The arrow marks indicate the direction of an increasing degree of water fouling. LCC/$LCCO_2$ are found to be more noticeably affected by differences in water quality than differences in the maintenance method (standard or optimal maintenance).

Risks imposed by varying energy unit prices

Because the ESCO project is committed to a contractual period of 10 years, the electric power and gas rates are likely to vary in the meantime, resulting in changes in LCC and hence in business economics. Figure 10 presents an evaluation of the cost advantages of triple-effect absorption chillers and turbo chillers against changes in the electric energy charge and gas unit price.

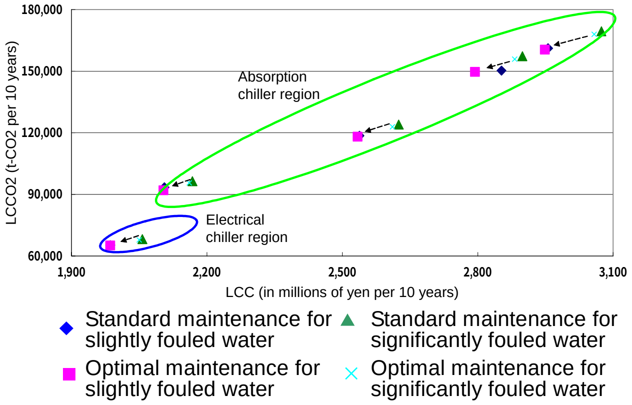


Figure 10. Relation between LCC and $LCCO_2$

In the figure, the upper-left region above the continuous solid line denotes the region in which electric turbo chillers come more advantageous than gas chillers. Figure 11 demonstrates that turbo chillers are more advantageous under the present conditions of review. Moreover, the less the cooling water is fouled, the wider the area where turbo chillers are effective.

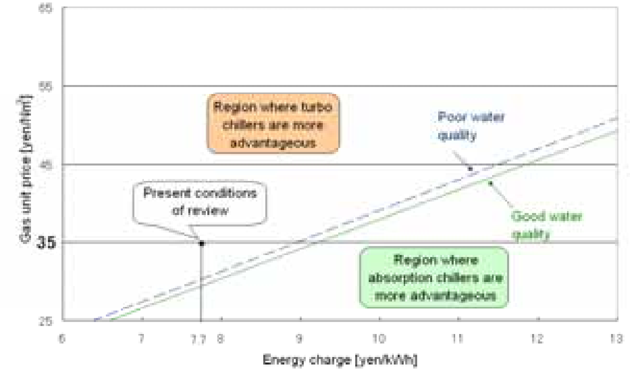


Figure 11. Decision criteria for making energy choices

CONCLUSIONS

This study has conducted an LCM evaluation of turbo, double-effect absorption and triple-effect absorption chillers and, what is characteristic, has demonstrated quantitative measures of reductions in both LCC and $LCCO_2$. Information derived from this study includes:

1) Depending on combinations of cleaning methods and their frequencies, optimal maintenance patterns exist to suit specific refrigerator types.
2) Absorption chillers coupled with neutral detergent cleaning conducted every year and chemical cleaning conducted at 4-year intervals minimize both LCC and $LCCO_2$.
3) Turbo and triple-effect absorption chillers virtually equaled in their evaluation of LCC, but electrical chillers prove better when it comes to minimize $LCCO_2$.

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