ASHRAE Journal

Economic Analysis of Hybrid Chiller Plants

By Brian Smith

Traditionally, chiller plants in large facilities consisted of constant-speed, electric-drive centrifugal chillers because they were the least expensive and most efficient option. Although natural gas was cheaper than electricity on a $/Btu basis, the price difference wasn't sufficient to offset the efficiency and capital-cost differences between electric and non-electric chillers.

In the past few years, the metrics have changed. Today, hybrid chiller plants using multiple chillers and different energy sources are being considered in many applications. What has changed?

Chiller Type	IPLV[1] (COP basis)	Capital Cost Δ[2]
Electric-Driven, Constant-Speed Centrifugal	7.0	Base
Electric-Driven, Variable-Speed Centrifugal	9.9	+25%
Electric-Driven Screw	7.5	0%
Gas-Engine-Driven Centrifugal	2.4	+280%
Steam-Turbine-Driven Centrifugal	1.5	+285%
Steam-Driven, Single-Stage Absorption	0.8	+35%
Gas-Driven, Two-Stage Absorption	1.1	+220%

1. IPLV values are general indicators of chiller efficiency at both design and off-design conditions and offered for comparison only. In the actual analysis, specific energy consumption values for each operating condition were used.
2. Capital Cost Δ includes chiller, pumps and tower, but not boiler.

Table 1: Typical water-cooled chiller efficiencies and costs.

A significant factor is the new time-of-use rate structures that electric utilities are implementing. While these new rate structures vary among utilities, users generally pay a lower rate when electricity demand is low (off-peak periods) and a much higher rate when demand is high (on-peak periods).

For example, some utilities have moved to real-time pricing (RTP), which is a pricing schedule where rates are determined a day or two in advance of their use. RTP rates eliminate or reduce demand charges. However, their presence is felt in the peak pricing of electricity. High on-peak prices are the primary means for electricity producers to recoup the cost of their peaking plants. With RTP, the price of electricity fluctuates with market demand and the weather, because high demand for electricity and warm weather tend to be synchronous.

Thus, owners, managers, and designers of large facilities exposed to these rate structures are recognizing that the biggest opportunity to reduce energy costs is to reduce the high-cost, on-peak use of electricity by their HVAC systems. In non-residential facilities, chillers are one of the largest energy users, so they are receiving a lot of attention.

Hybrid chiller-plants are being evaluated because they use multiple energy sources. In markets where high on-peak electricity rates exist and natural gas prices are low, a combination of electric and non-electric chillers may make the most sense from a long-term economic perspective.

This article tries to answer the question, "How high must electricity prices be to justify a hybrid chiller plant?" In the following economic analysis of hybrid chiller plants, we first established a baseline of relative chiller efficiencies and capital costs, according to data from multiple manufacturers. Next, we selected an industrial user rate for natural gas, which we held constant throughout the analysis. Then, we varied the peak price of electricity to test the sensitivity of various chiller combinations to progressively higher on-peak electric prices. Finally, we analyzed life-cycle costs, comparing the operating cost savings to the additional capital costs. From these calculations, we drew some general conclusions about hybrid chiller plants that will help engineers evaluate their feasibility from a long-term economic perspective.

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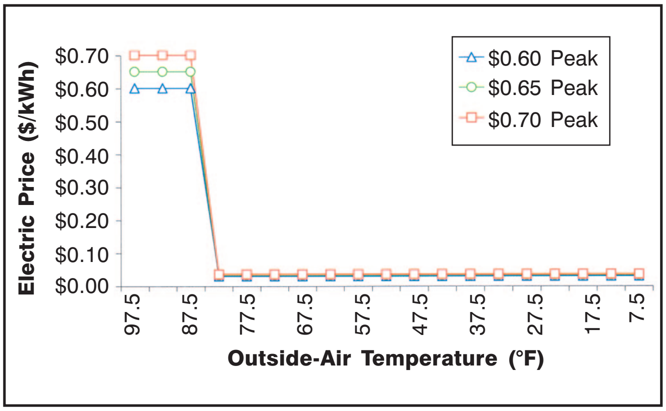

*Figure 1: Temperature-based rate structures.**

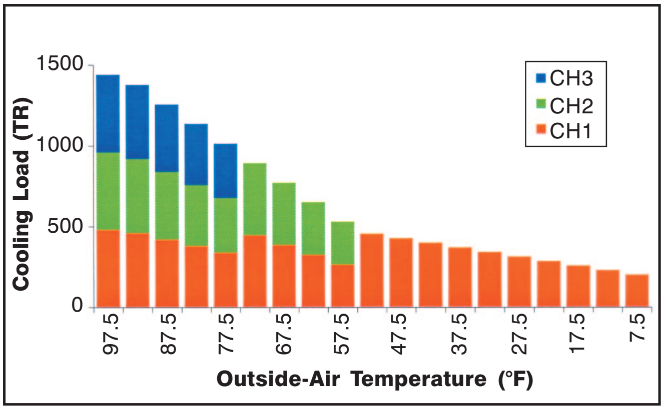

*Figure 2: Chiller-plant load profile.**

This is a theoretical analysis based on broad market trends, and is not intended as a study of actual utility rate structures. It is offered as a design guide, not as definitive criteria for hybrid chiller plant specifications.

Inputs Used in the Analysis

First, let's look at the inputs used in this analysis, starting with the types of chillers examined. In the analysis, we used a plant consisting of three 500-ton (1760 kW) chillers, with associated pumps and towers. The chiller types used are listed in *Table 1*.

Note the wide differences in efficiency, represented by the integrated part-load value (IPLV, as described in ARI Standards 550/590 and 560). IPLV, originally developed as a performance measure for single-chiller plants, has also been shown to apply equally well to multiple-chiller plants.[1,2] To simplify comparison among various chiller types, we converted all IPLVs to a coefficient of performance (COP) value, with the higher values equating to higher efficiency and lower energy consumption. Also, note the significant range in capital costs (purchase and install) of the various chiller types. This table shows why electric-driven chillers have been a popular choice in large-tonnage chiller plants for many years.

However, as we know from field experience, on-peak electricity prices that are much higher than the cost of natural gas on a $/Btu basis can make non-electric chillers a viable option.

In our analysis, we used four hypothetical electricity rate structures. We looked at a traditional structure, with a usage price of $0.07/kWh and a demand price of $10.00/kW. Then, we undertook the sensitivity analysis by looking at the impact of three progressively higher rate structures related to outdoor temperature, illustrated in *Figure 1*.

While we know of no real-life electricity rate structures that are explicitly temperature-based such as ours, we believe the correlation between outdoor temperature and on-peak demand for electricity is implicit in all RTP rate schedules. So we have created these hypothetical, temperature-based rate structures to predict how often on-peak prices will be charged.

For the purpose of our analysis, we made additional assumptions: zero inflation and zero energy escalation; average weather data for the United States; the chillers are piped in a parallel arrangement; there is no airside economizer, so the chillers run year-round; the plant runs 24-hours-a-day and seven-days-a-week, typical of large institutional and industrial facilities that might consider a hybrid chiller plant; the electricity rate structures are in effect on weekends and holidays, as well as during the week; and each plant has a full-service maintenance contract that is based on the components it contains. The chiller plant load profile, shown in *Figure 2*, is hypothetical but typical of many buildings.

Energy Analysis

Based on these assumptions, chiller plant performance was analyzed using a chiller plant energy-estimating software tool that uses the ASHRAE temperature-bin method, plus equipment efficiencies from a number of manufacturers, to estimate chiller-plant energy consumption for each temperature bin, which is then summed to establish the total energy consumption.

Financial Analysis

The chiller plants were analyzed on a life-cycle-cost basis. Plants with higher efficiencies usually had an added capital cost, which we compared to their energy and maintenance costs. Since costs and savings occur at various times during the life of the chiller plant, we calculated them based on net present value (NPV), which brings all cash flows back to present dollars. For the NPV calculations, we assumed a 10% discount rate and a 25-year chiller-plant life.

Sample Analysis

Using our traditional rate structure ($0.07 kWh usage and $10.00 kWh demand), we compared a base plant consisting of three electric-driven, constant-speed centrifugal chillers to a hybrid plant which uses two electric-driven, constant-speed

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* (°F – 32) ÷ 1.8 = °C

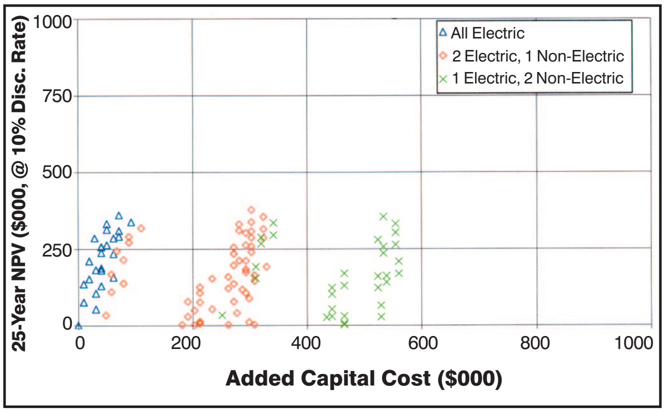

Figure 3: Case A, $0.07/kWh usage and $10.00/kW demand for electricity and $0.40/therm for gas.

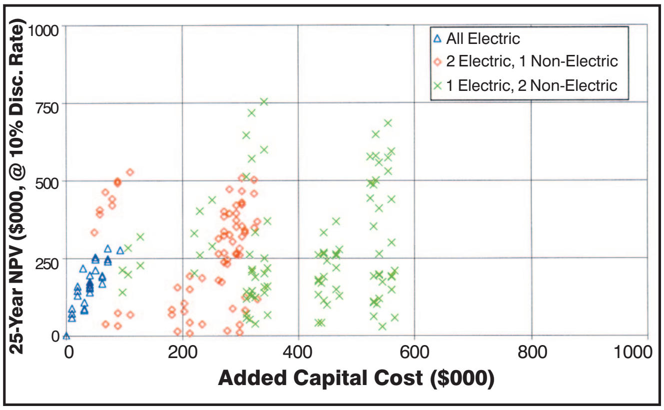

Figure 4: Case B, $0.60/kWh temperature-based rate for electricity and $0.40/therm for gas.

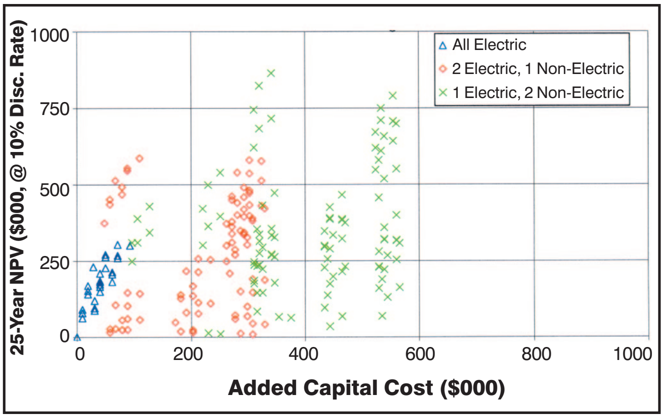

Figure 5: Case C, $0.65/kWh temperature-based rate for electricity and $0.40/therm for gas.

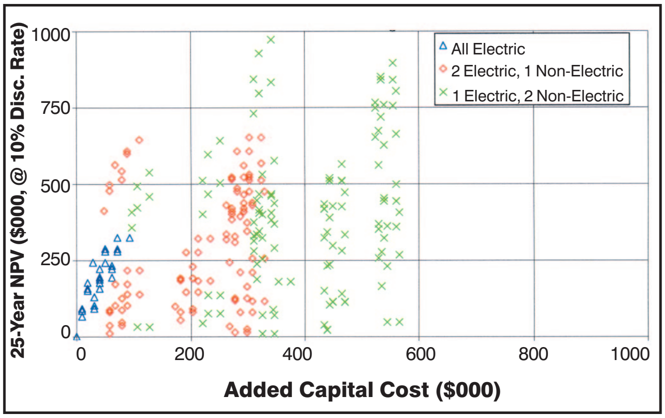

Figure 6: Case D, $0.70/kWh temperature-based rate for electricity and $0.40/therm for gas.

centrifugal chillers and one steam-driven, single-stage absorption chiller as the peaking chiller (meaning "last on-line"). When we ran the analysis, we found that the economics are poor: an added capital cost of $48,000 and a 25-year NPV of $33,000. Obviously, this plant would never be considered.

However, using the temperature-based rate structure, if the maximum electricity price were $0.70/kWh, we found that we would have a very compelling economic case: for the same added capital cost of $48,000, the 25-year NPV is an impressive $412,000. This plant would definitely be considered.

Complete Analysis

Using our analysis software, we evaluated more than 280 equally sized chiller combinations, including constant- and variable-speed electric centrifugal, electric screw, steam-turbine centrifugal, gas-engine centrifugal, single- and two-stage absorption chillers. Every possible configuration of chiller sequencing was used, allowing six permutations of each chiller plant:

1. CH1 – CH2 – CH3
2. CH1 – CH3 – CH2
3. CH2 – CH1 – CH3
4. CH2 – CH3 – CH1
5. CH3 – CH1 – CH2
6. CH3 – CH2 – CH1

In real-world operation, it is possible to use direct digital controls to sequence a chiller plant to take advantage of the lowest energy rates and most efficient chiller. However, in this analysis, we chose to let the software-generated numbers provide an objective guide, rather than apply our own subjective understanding.

In our sensitivity analysis, we used the traditional usage-and-demand rate structure described earlier as Case A, and the three temperature-based electric rate structures as follows: $0.60/kWh maximum as Case B, $0.65/kWh maximum as Case C, and $0.70/kWh maximum as Case D. In all four cases, to highlight the effect of changing electricity prices, we assumed a constant rate for natural gas of $0.40/therm[3] and a constant boiler efficiency of 80%. For each plant and rate structure, we calculated and plotted the 25-year NPV as a function of added capital cost. In *Figures 3–6*, we can quickly see the impact of varying the electricity costs, and then draw some general conclusions. While 280 chiller combinations were analyzed, only those with positive NPV were plotted in *Figures 3–6*.

Using our traditional rate structure (Case A), we see that many of the hybrid plants have significantly higher added capital costs than the all-electric plants, but they do not offer any real advantage in terms of better NPVs. Under this rate structure, most designers and owners would choose to stay with an all-electric plant.

As we move to a temperature-based rate structure with a $0.60/kWh maximum (Case B), we can see that some hybrid plants with one non-electric chiller can generate approximately $500,000 in NPV savings for an added capital cost of $100,000 or less. Under this rate structure, where the maximum electricity price exceeds the gas price by a multiple of 44 on a $/Btu basis, some designers and owners might consider a hybrid plant, depending on their operating and financial goals.

In Case C, we raise the temperature-based rate structure to a $0.65/kWh maximum cost for electricity (an electricity-to-gas price multiple of 48). We now see that hybrid plants with two non-electric chillers also offer attractive NPVs. Under this electricity rate structure, hybrid plants would clearly deserve evaluation. There are now a variety of chiller combinations that could be considered, depending upon operating and financial objectives.

In Case D, we consider the impact of a temperature-based rate structure with a $0.70/kWh maximum cost of electricity (a price multiple more than 50). Here, the economics in favor of hybrid chiller-plants would be extremely compelling. Hybrid plants with two non-electric chillers could now offer tremendous NPVs — some approaching $1 million.

Conclusions

While traditional usage-and-demand electricity rate structures often do not favor hybrid chiller-plants, it is clear that a trend toward time-of-use rate structures would change the metrics. If on-peak electricity prices exceed concurrent gas prices by a multiple of 40 or more on a $/Btu basis (which is not unheard of), a hybrid plant should definitely be considered.

The financial performance of hybrid plants varies significantly with the types of chillers used. Note again the wide differences in COP and capital cost among the chillers used in our analysis. Fortunately, when it comes to selecting the optimum chiller-plant combination, there are software tools available that can simplify the process.

References

1. Hubbard, R.S. 1999. “Forum on ARI Standard 550-590-98.” *Heating, Piping, Air Conditioning Magazine* May.

2. Hubbard, R.S. 1999. “Not-so-chilling results.” *Engineered Systems* September

3. 2002. “Average price of natural gas sold to industrial consumers ….” *Energy Information Administration/Natural Gas Monthly* March.

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