Sizing CCHP Systems for Variable and Non-coincident Loads, Part 2: Operating Strategies

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ABSTRACT

One serious challenge to the implementation of combined cooling, heating and power (CCHP) systems is matching and sizing the system to strongly and frequently varying load conditions. Previous works, part 1 of this work in particular, have proven that while CCHPs have significant cost and performance advantages over traditional single-cycle systems, inadequate strategies, failure to address system flexibilities to accommodate load variations in particular, seem to have negatively impacted this promising technology. This paper discusses some techniques that can improve system flexibility for variable and non-coincident loads.

Key words: CCHP, challenges, heat recovery, part load, efficiency

BACKGROUND

It has been shown in part 1 of this paper that developing a design strategy for CCHP systems to mitigate load fluctuations to provide a cross platform selection criteria is a complex matter; the advantages of CCHP systems are not as obvious as is suggested by the thermodynamics. It may be possible to integrate a CCHP system into a site that experiences hourly load variations and non-coincident loading by implementing strategies that complement traditional base loading strategy. Sites experiencing seasonal variation and non-coincident loading may have energy demands that are better satisfied, with much greater flexibility, by implementing a thermal/electric load partitioning strategy. More research would be required to determine the extent to which installing more complex controls and scheduling routines increases the cost of implementing prime mover alternation or thermal/electric (T/E) load partitioning CCHP operating strategies as compared with a typical base loading strategy. The general rule of CCHP is upheld however, as with all CCHP systems, the overall feasibility and efficiency of CCHP systems designed to meet variable and non-coincident loads depends on the extent to which power is used, and heat is generated, recovered, and utilized.

OPERATING STRATEGIES

Different strategies have been developed to address the challenges posed to traditional CCHP system designs by load profiles characterized by hourly, daily, and seasonal variations, as well as non-coincident loading. The strategies discussed in this paper are load targeting, energy storage systems, prime mover alternation, and thermal/electric load partitioning. They have the same overall goal of retaining high system efficiency independent of the site load (Figure 1).

Load Targeting

The most traditional and most broad (although not necessarily the most beneficial) operating strategy for a CCHP system—including those sites that experience variable or non-coincident loading—is that of load targeting. The strategy is to size the output of the CCHP system—either thermal or electric—to match some predefined load—thermal or elec-

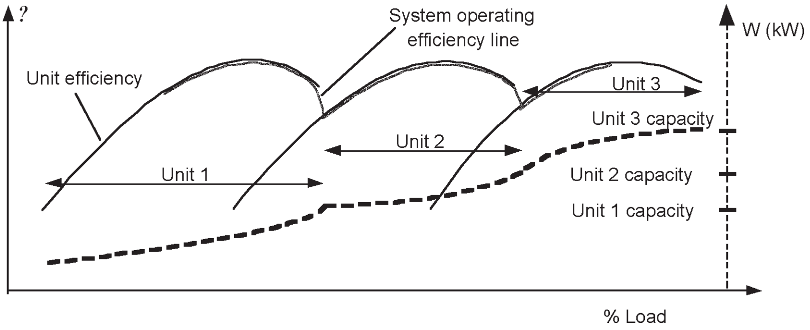

Figure 1. System efficiency and site load variations.

tric—onsite.

This strategy encompasses both the topping and bottoming cycles and also the concepts of load following and stand alone island. The topping cycle primarily targets an electrical load and applies the leftover energy to a thermal load. The bottoming cycle primarily targets a thermal load and uses the leftover energy to generate electricity.

A topping cycle may be used to provide electrical power as a response to site electrical demand. In this case, the electrical output of the prime mover follows the load of the facility. The concept is that the prime mover will fulfill a large portion of site electrical demand during all operating hours. Alternatively, the prime mover may also generate power at some level exceeding site demand during all operating hours. Now the site is operating as an island because it never requires power from the utility grid. The main benefit of load targeting is that the system is relatively simple to design and implement. This strategy typically requires the least amount of ancillary equipment and, therefore, space.

A system designed to operate based on the load targeting strategy is perfectly acceptable when the site does not experience strongly varying or non-coincident loading, but in these scenarios, the drawbacks of load targeting should be considered. When a prime mover operates in the load-following mode, it operates primarily at off-design conditions, where system efficiency is considerably lower. Similarly, the stand alone island operating strategy may not be permissible because of the economic considerations described previously.

A safe decision for a load targeting scenario—in the case of constant or varying and non-coincident loading—is base load targeting. This solution entails the monitoring of the site power load during times of minimal demand and matching the power output of the prime mover to this value. The benefit is that the prime mover will be able to run at full load and near peak efficiency throughout its operating hours. However, for optimal economy, the site must have a thermal load during these periods, when it can use the waste heat of the prime mover.

Energy Storage

Another traditional operating strategy for a CCHP system at a site experiencing variable or non-coincident loading is the use of energy storage. The energy storage system may be in the form of thermal energy—such as hot or chilled water tanks—or electrical storage—such as batteries. The strategy is to size the storage system to fulfill site demand during the times when site loads cannot be satisfied by the CCHP system, and then to size the CCHP system to fulfill the demand of the site plus the energy storage system during the times it can satisfy the site loads.

A thermal energy storage system that has become more popular because of economic factors—particularly the adoption of time-of-use rate schedules by utility companies—is the use of stored chilled water for cooling. In these systems a chiller is used—typically during off-peak operating hours when electricity for utility customers on time-of-use rate schedules is cheaper—to chill or freeze water and store it in tanks.

A CCHP system may be used to fulfill the demand of either, or both, a high or low temperature energy storage system. For a high temperature heating hot water system, the heat from the CCHP system can be recovered using a heat exchanger, by the water that feeds directly into the storage tank. For a low temperature chilled water system, the heat from the CCHP system can be recovered and used in an absorption chiller to generate either water or ice that feeds directly into the storage tanks. If a combination of systems is desired, a prime mover with sufficiently high temperature exhaust could be used to produce heating hot water, and the remaining energy in the exhaust might be used by a smaller absorption chiller. Conversely, another possibility would be to use high temperature exhaust heat in an absorption chiller and use the remaining heat in the exhaust to produce and store service/domestic hot water (DHW).

A more common scenario would be to store only one form of thermal energy and use the other on an ongoing basis. This strategy would be useful at a location that always requires cooling (and/or dehumidification), such as a clean room. The second method would be to store the chilled water and use the hot water or steam as it is required. Thermal energy storage systems may require a large volume of space (i.e., in cases where the facility may be rented, excavating the site for underground storage for instance, may be prohibited).

Electrical storage systems in general, and batteries in particular, can be insufficient for storing the large amounts of power CCHP systems are capable of generating because of limits on the depth of charge and charge/discharge cycling limitations.

Prime Mover Alternation

A CCHP system design and operation strategy that is less traditional, but that may suit the demands of a site experiencing variable or non-coincident loading, is termed a prime mover alternation. Prime mover alternation is similar to the load-following operating strategy, but uses multiple prime movers to maintain a higher operating efficiency. With this strategy a number of prime movers are installed so that their cumulative output capacity—thermal or electric, depending on whether the system is sized for topping or bottoming—is equal to the maximum site demand. The strategy generally takes two forms: additive and substitutive.

The additive form of the prime mover alternation strategy is comparable to the load-following strategy, but with a number of smaller prime movers installed in place of a larger prime mover. As site demand increases or decreases, more prime movers turn on or off to match the demand and, during most operating hours, multiple prime movers are turned on simultaneously. This strategy lends itself to a variable load, where the thermal and electric loads are required at the same time. One or more prime movers may operate continuously to satisfy the site's base electric or thermal load and, as the load increases, more prime movers may come online to match that demand. As the load decrease, some of those prime movers may drop offline to match the demand.

There are a number of benefits to the additive prime mover alternation strategy. The first is that the prime movers can be controlled in such a way that they come online when site demand is within a specified percentage of their full output capacity. In this way the prime movers can be operated near full load, where their efficiency is the highest, throughout most of their useful life. This should be contrasted with a typical load-following scenario in which one large prime mover, sized for maximum site demand, operates at part load—and thus lower efficiency—during most of its useful life. The second benefit of the additive prime mover alternation strategy relates to the maintenance of the prime movers. Because the site demand is fulfilled by a number of prime movers—as opposed to one large unit—it may be supplied with some percentage of its demand even during times when one or more prime movers require maintenance or, in the worst case scenario, replacement. A system with one large prime mover would be completely disabled if the unit were taken offline for maintenance or replacement.

The drawbacks of the additive prime mover alternation strategy are (1) cycling of the prime movers and (2) additional costs for ancillary materials and labor. Because of the nature of the operating strategy, most of the prime movers would be cycling on and off throughout the operating hours. For some prime movers, such as gas turbines, a preset amount of time is required between shutdown and startup to preserve the life of the equipment. Such equipment is not well suited to this operating strategy because it cannot respond quickly to fluctuating site demand. Because of the requirement for installing more prime movers, additional piping, conduit, controls, structural materials, and possibly heat exchangers, may need to be installed to provide the system with sufficient flexibility. These expenses may drive up the cost of the CCHP system beyond that of a single load-following scenario with one large prime mover. In that case, it would be important to consider the avoided costs of purchasing power and fuel for heat during downtime, as well as the savings accrued from utilizing a higher efficiency system.

The substitutive prime mover alternation strategy is also comparable to the load following strategy and uses smaller prime movers in place of one large unit. As site demand increases or decreases, different prime movers turn on or off to match the demand and only one prime mover operates at any given time.

After gaining an increased understanding of the loading scenarios and mitigation strategies, combined with equipment options and complex utility tariffs, it becomes easy to see why traditional CCHP design strategies struggle to accommodate site needs.

The disadvantages of the prime mover alternation strategy are cycling of the prime movers and additional costs for ancillary materials and labor. Due to the nature of the operating strategy, each of the prime movers would cycle on and off at least once a day. If the site has two heating demand peaks, then the prime mover serving those demands would cycle on and off at least twice each day. As in the additive strategy, this limits the choice of prime mover.

Thermal/Electric Load Partitioning

The strategy of dividing either an exclusively electric or thermal load into both electric and thermal partitions is known as thermal/electric load partitioning. The objective is to divide an existing load into new partitions that match the electric and thermal outputs of a CCHP system. The power generated by the CCHP system would supply the electric load partition and the heat in the CCHP system exhaust would supply energy to the thermal load partition.

In some utility rate climates, such as in California where rates are among the highest in the nation [1], thermal/electric load partitioning makes good sense. This is easy to visualize in terms of a cooling load served by mechanical chillers. A 750 ton cooling load, served by a bank of three chillers operating with an efficiency of 0.75 kW/ton, would require 1,000 kW of power to operate at full load. If the chillers must operate during peak hours, they represent 1 MW in demand charges. This electrical energy use, and associated charges, could be reduced by implementing a thermal/electric load partitioning scheme, where the electric output of the prime mover powers some portion of the existing chiller bank, and the thermal output of the prime mover supplies energy to an absorption chiller. In this case the absorption chiller is not a replacement for the mechanical chiller(s), but a complement. If the prime mover and absorber are sized to match the cooling load, then it would be possible to avoid all electrical costs associated with operating the chiller bank.

Theoretically, a heat load may also be partitioned into thermal and electrical parts. A facility with electric boilers may benefit from installing a CCHP system to generate electricity to energize some of the boilers with the exhaust heat recovered to generate steam, or hot water to offset other boilers. The prevailing utility rate climate generally discourages electric heating, which is also generally less efficient than heating with fossil fuels.

This strategy also lends itself to sites that experience seasonal load variations, or sites that may require simultaneous heating and cooling. At these sites, implementation of a CCHP system with an exhaust damper actuator/diverter valve will allow the modulation of exhaust gases. In the cooling season, the energy in the exhaust gases may be recovered for use in an absorption chiller. During the heating season, the energy in the exhaust gases may be recovered for the production of steam or hot water. In facilities that require both heating and cooling simultaneously—such as universities or some manufacturing facilities with laboratories or clean rooms—the exhaust damper actuator could direct some portion of exhaust gases to the energy recovery systems of the absorber, and steam or hot water heat exchanger, simultaneously. A more traditional approach to the same concept is to pass all exhaust gas through a heat recovery steam generator. The steam flow is then modulated between heating applications and absorption cooling, as appropriate. The approach in which exhaust gas is used in lieu of the conversion to steam for an absorption chiller has been used in this discussion based on the relatively recent development of absorption chillers that can accept exhaust gas as the heat source and the fact that these systems are more efficient from an exergy perspective.

The main advantages of the thermal/electric load partitioning strategy are that it maximizes the output of the CCHP system and can introduce a degree of flexibility that will allow it to respond to varying thermal loads. Partitioning the loads means that the overall CCHP system size may be much smaller than that of a system designed to match either a thermal or electric load. Instead of designing and paying for a CCHP system to match a peak load, this strategy reduces the output capacity to be proportional to the ratio of electric to thermal output for any given prime mover.

The primary disadvantage of the thermal/electric load partitioning strategy is that construction is likely to be much more expensive as a result of additional equipment, controls, and space that may be required.

Hourly, daily, and seasonal schedules may each have the same total idle percentage in a year, but the total charges would vary because of utility demand and peak charges. To demonstrate a CHP system that experiences load variations and non-coincident loading, a few case studies will be examined.

CASE STUDY: A HOTEL

Consider a hotel in Hawaii: Because the occupancy conditions can vary strongly on an hourly and seasonal basis, so does the need for heat and power.

The climate of Hawaii is such that little space heating is required, although there is a large cooling and dehumidification load that must be satisfied every day. The magnitude of this load varies with the time of the day. Because the facility is a hotel, it is occupied primarily at night and mostly unoccupied during the day. The occupancy pattern of the hotel also adds complexity by inducing non-coincidence between thermal and electric loads in the form of domestic hot water (Figure 2). The primary thermal load is for DHW required for showers, typically in the mornings between 6 a.m. and 8 a.m. and in the afternoons, roughly between 4 p.m. and 6 p.m. Generally these DHW peaks fall outside of the period for peak cooling load.

The hotel typically experiences high occupancy ten months of the

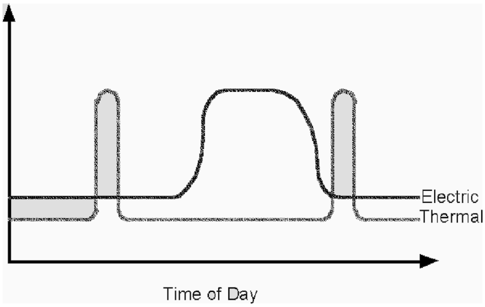

Figure 2. Hourly Variation and Non-coincident Load Profile.

year and lower occupancy in December and January. The effects of this seasonal variation on CCHP system selection are mitigated because of the excess electricity that can be sold to the local utility.

Therefore, the system(s) can be designed based on typical loading during the ten busier months of the year. Table 1 presents a summary of the hourly and seasonal load variation.

Table 1: Seasonal Loading Percentages

	February-November		*December & January*	
	Day	*Night*	*Day*	*Night*
Electrical Load	100%	30%	90-100%	20%
Thermal Load	100%	20%	90-100%	10%

The energy needs of the hotel are currently served by an integrated heating/cooling hydronic system, shown in Figure 3. In this system a mechanical chiller is used to provide chilled water for cooling and dehumidification to the hotel. Heat is recovered from the chiller by city water, as a means of preheating the DHW with additional heat picked up from a water source heat pump before being stored for use onsite in a hot water tank. When the hot water tank receives the call for water, it passes through propane-fired gas heater to ensure that it is delivered at the correct temperature. The cooling side of the heat pump is used to pre-cool a portion of the water sent to the chiller, and final cooling of the chiller is accomplished by using an onsite injection well.

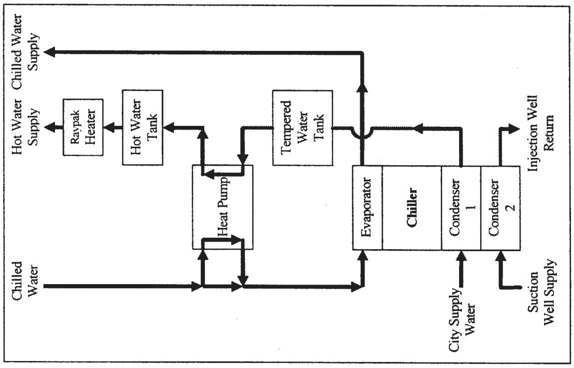

Figure 3. Existing energy system.

Recommendations

The variable and non-coincident load requirement at this hotel is more tolerable because the small local utility is willing to purchase power generated in excess of site needs. Based on the equipment selection strategies described previously, this site is a candidate for load targeting, storage systems, prime mover alternation, and thermal/electric load partitioning. These options will be prioritized below to determine the best possible solution for the hotel.

To maximize the performance of a CCHP system by operating the prime mover at full load, the load targeting strategy has two options. One option is to size the system for the hotel's base load. This ensures constant operation year round, with all power and heat being used on-site. The second option is to size the system for the site peak electrical load (because electricity is much more expensive than fuel), and sell excess electricity to the utility. The problem with the second option is that the waste heat generated by the system is not likely to match the thermal load of the facility and, with the system sized for the peak, a large portion is likely to be exhausted throughout the year. This quantity of unrecovered waste heat will dramatically decrease the overall system efficiency. In localities where CCHP systems are supplemented with incentive funding, this drop in system efficiency may fail to meet required program goals.

Energy storage systems are always an option from a thermodynamic perspective, but they present new problems in the realm of the resort hotel experience. At such a location, real estate may be the prime motivation for visitors and the hotel develops their real estate investment by providing beaches, pools, gardens, and golf courses for their customers.

Because of the presence of the non-coincident load, the prime mover alternation strategy may be an option. System sizes and designs will vary, but there are possibilities for two and three prime mover systems. There are two methodologies for satisfying the load with this strategy. The first possibility is to install the base load targeting system described previously. That CCHP system would run continuously at full load throughout the year. A second system could be installed, sized to match the thermal output to the cooling load—or some portion of it—via an absorption chiller. Once a day, as the cooling load reaches some predefined value in the energy management system (EMS), the secondary CCHP system would cycle on and turn off with another signal at night. Two configurations of this strategy are shown in Figure 4.

The configuration could be expanded to a third prime mover, sized for the DHW peaks. This system could be controlled by a time clock, or EMS program, to run in the hours just before and just after the cooling load, to generate heat for DHW. In this configuration, one prime mover would operate continuously with two smaller prime movers that would cycle daily. The other configuration would involve the same base load prime mover, but larger units for the cooling and heating loads. In that configuration, the base load unit would cycle off at the time the cooling load begins to increase. At that time, a prime mover sized for the cooling, plus base loads, would cycle on and operate until the signal is received that the cooling load peak is sufficiently passed. When the peak is passed, the base load prime mover would cycle back on. Two configurations of this strategy are shown in Figure 5. Adding the third prime mover, sized for the DHW load plus the base load, would decrease the hours of operation for the smallest prime mover sized for the base load.

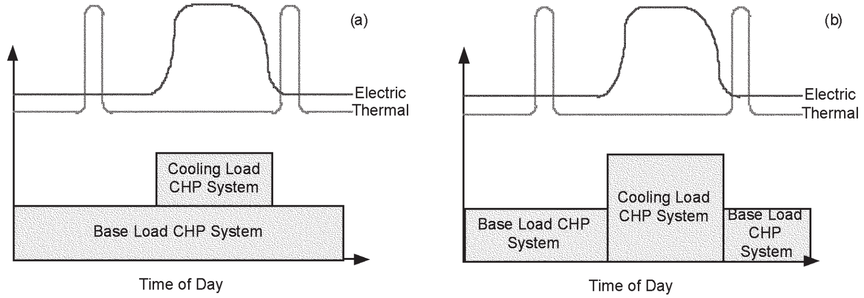

Figure 4. Prime mover alternation with two units

The first system is better from an economic and engineering standpoint. Both systems require the purchase of a base load targeting prime mover of the same capacity. However, the continuous operating hours in the first system will allow it to pay back in a shorter amount of time. Because the units sized for the DHW and cooling loads in the second system must compensate for the base load, they will be much larger and more expensive than those smaller units in the first system. Because of the larger, more expensive capacity, and shorter run hours, these units would take longer to pay back. Additionally, from an engineering and maintenance perspective, the configuration that reduces the on/off cycling of the prime movers is better suited to equipment preservation.

The load partitioning strategy may be another method to mitigate the non-coincident variable load of the hotel. This strategy would involve coupling a single prime mover to an absorption chiller. Because of the relative price of electricity to gas, it would be prudent to size the prime mover to the cooling load and maximize cost savings. In this strategy, the heat from the prime mover would be recovered in an absorber to decrease the cooling load with electric power supplying the mechanical chillers with energy. This design decreases the generation capacity required of the prime mover—and thus cost—because less than 100% of its electrical output is required to power the mechanical chillers, Figure 6.

Another possible, but more complex strategy, would involve coupling a single prime mover and diverter valve to both an absorption chiller and heat exchanger. When the cooling load is low and the DHW demand is high, the diverter valve could redirect heat from the absorber to an air/water heat exchanger, Figure 7. Aside from the problem that the heat recovery sized for the absorber is not likely to match the DHW load, a more serious issue would be that the electric

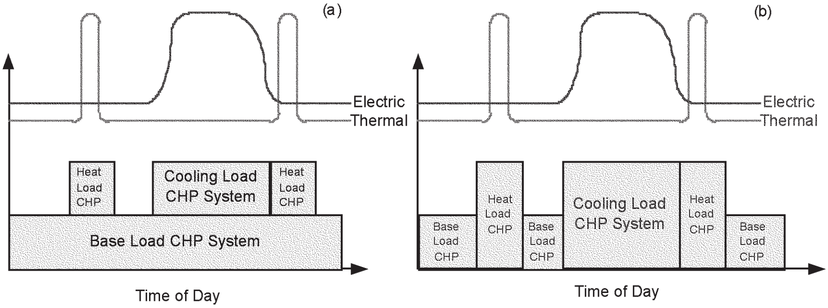

Figure 5. Prime mover alternation with three units.

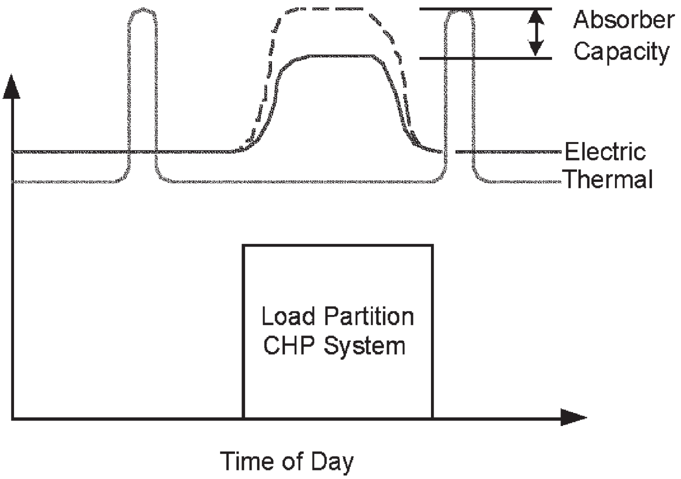

Figure 6. Single Prime Mover Load Partitioning System Used to Decrease the Electric Chiller Load.

output of the CCHP system may be much more mismatched to the site demand when the cooling load is low. Fortunately, at this particular facility, that extra electricity could be sold to the local utility. However, that luxury is not often available on the mainland, and the low site electric demand would cause the prime mover to operate at part load. In the part load regime the efficiency drops and the heat produced may not be enough to satisfy the DHW load that was originally targeted. Moreover, these load partitioning systems could be installed on top of a base-loaded prime mover. Possible configurations of this strategy are depicted in Figures 8 and 9. This strategy would reduce the installed cost by decreasing the capacity required of the additional prime movers.

The drawbacks of implementing this strategy for this specific case are the costs of the system and the efficiency at which it would operate. A diverter valve can be very expensive and the cost of additional prime movers, absorbers, and heat exchangers will significantly increase the price. Furthermore, because the prime mover would be sized for one load, the efficiency is likely to drop off when serving the other. This is because—with such small loads relative to large MW scale facilities—there are periods when the output of even small kW scale prime movers may exceed site demand. Overall CCHP plant efficiency could be improved by adding the load partitioning system on

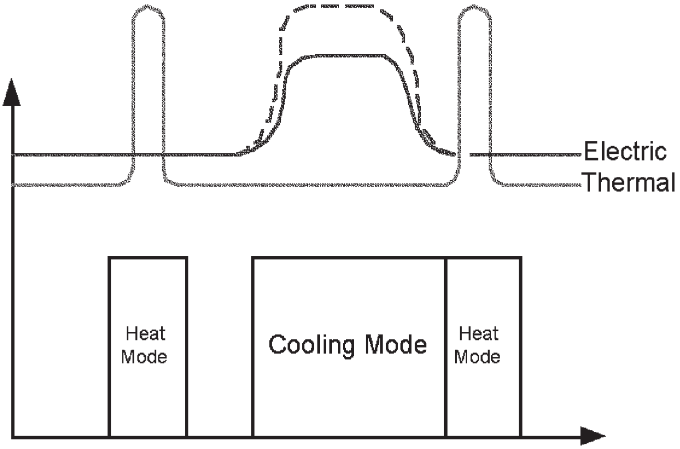

Figure 7. Single Prime Mover Load Partitioning System with Diverter Valve to Serve Heat and Power Loads.

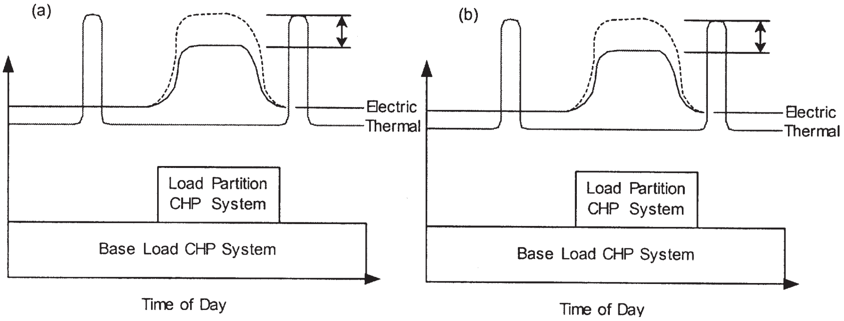

Figure 8. Dual Prime Mover Load Partitioning System.

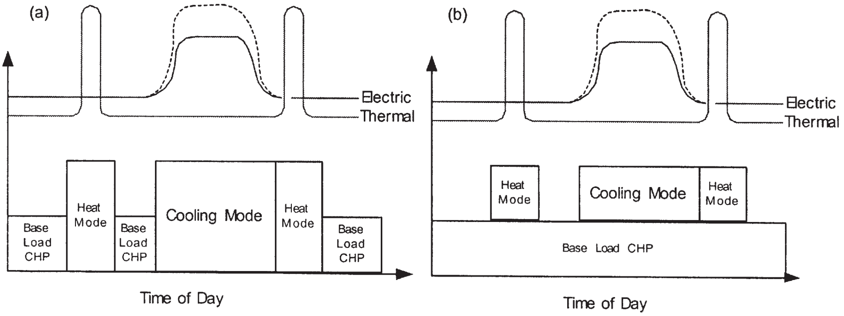

Figure 9. Dual Prime Mover Load Partitioning System with Diverter Valve.

top of a base-load system, but in that case, the benefits over the load partitioning strategy are marginal given the higher price tag.

Based on these options, the recommendations for the CCHP system at the hotel in Hawaii are prioritized. The best engineering solutions based on the ability to meet site demand and system efficiency:

i. Prime mover alternation with a continuous base load system
ii. Prime mover alternation with all systems cycling
iii. Load partitioning system for cooling with a base load system
iv. Load partitioning system for cooling without a base load system
v. Load partitioning system for cooling and heating with a base load system
vi. Load partitioning system for cooling and heating without a base load system
vii. Load targeting system designed for the base load
viii. Load targeting system designed for the peak load
ix. Prime mover with energy storage systems

The best economic solutions based on installation cost and savings:
i. Load targeting system designed for the base load
ii. Prime mover with energy storage systems
iii. Load targeting system designed for the peak load
iv. Prime mover alternation with a continuous base load system
v. Prime mover alternation with all systems cycling
vi. Load partitioning system for cooling without a base load system
vii. Load partitioning system for cooling with a base load system
viii. Load partitioning system for cooling and heating without a base load system
ix. Load partitioning system for cooling and heating with a base load system

From these qualitative lists, the system that ranks highest on both is the system that implements prime mover alternation with a continuously operating base load system. This system would satisfy the largest portion of site demand, thus securing the largest portion of savings, at the lowest cost for the non-traditional CCHP operating strategies.

CASE STUDY: A UNIVERSITY

The most complex CCHP load conditions not only vary with time and are non-coincident, but they also vary seasonally, so that the basic CCHP equipment required to satisfy site energy loads in one season may not operate in the next season. Consider data collected from a university campus in northern California:

The university has an annual electrical peak demand of about 8 MW and is anticipated to grow to about 19 MW by 2020. The power requirements are met by the local utility and by an existing CCHP system, with two reciprocating engines producing about 2.3 MW and 290 KW, respectively. The remaining power, which is not produced by the CCHP system, is purchased at a cost of $2.3 million per year.

The primary thermal load of the university is for space conditioning; whereas the primary power load consists of lighting, mechanical chillers, plug loads, and other laboratory and miscellaneous equipment. The power load of the university is more consistent than the thermal load. However, the power load changes slightly in the summer, dropping to about 5 MW peak from May through October. The peak lasts about five hours and roughly coincides with the cooling load. The total current site cooling load is about 2,370 tons, including the 120-ton absorption chiller.

One of the problems of the existing CCHP system is its inability to respond to daily and seasonal variations in power and thermal demand—the latter having significant consequence on the efficiency of the system.

On a relatively warm day, when the campus does not require heat, there will be little heat exchange between the exhaust gas and the condensate return, resulting in negligible thermal recovery. The exhaust heat is then usually dumped to the ambient environment, at very high temperature. Such a steam loop may operate in a radically different scenario in the morning hours of the same day, when the heat load increases.

Now, consider a part of the day when the power load drops significantly for the same campus—say a weekend afternoon on a cold day. The campus power load drops, but the heating demand rises. The heating load necessitates a thermal output without a use for the excess power. The mismatch between power and thermal loads remains a serious challenge in the design and selection of CCHP systems, and it is difficult to design a low-cost system that satisfies drastically changing load profiles.

The above challenges are at times compounded by issues specific to the given site—for example, reciprocating engines may not be able to operate with economizers (i.e., they cannot recover the waste heat from the stack if the engine is equipped with a turbocharger). The turbocharger may conveniently boost the power output, but it may also increase the intake temperature of the engine so high that the intake temperature is not tolerated by the engine as it initiates detonation—colloquially known as "knock." The intake air may be cooled by a cooling tower to a convenient temperature of about 100ºF, which adds maintenance costs and complicates the system operation. In many cases, the state of low efficiency as a result of extended part-load operations on the power, heat, or both sides, could constitute a significant percentage of the overall operating hours—at times well over 50% during the summer—if the thermal load is used for space heating.

Recommendation

An ideal system would run near maximum efficiency during all these load scenarios, with minimum heat rejection to the atmosphere. Also ideally, the power produced onsite will be entirely used at the site. However, a system is often designed for a maximum heating scenario, i.e., operating at very low efficiency as the system heat load drops—reaching its worst phase during the transition and cooling hours when no heat is recovered. The only way to mitigate such a scenario is to have absorption chillers use the waste heat for cooling. This significantly increases the capital cost and often renders the system cost prohibitive. The choice of cooling, which requires absorption chiller, and heating, alternating from the same recovered heat source, is therefore the most likely, most flexible response to the given scenario—assuming the power load remains constant, or the CCHP system is sized for base power load. This illustrates the thermal/electric load partitioning strategy with the cooling load partitioned into parts that can be satisfied by electric and absorption chillers.

For the type of load assumed in the above hypothetical campus—with seven possible scenarios, and where cooling and heating can alternate or overlap—it is safe to generally assume that a combined cycle plant with an absorption chiller (Figure 10, or a combined cycle with multiple gas turbine engines, Figure 11), offers near maximum flexibility, which is demonstrated based on the seven energy load scenarios listed above, illustrated in Table 2.

Scenario 1 represents a very hot summer day with no heating required. In this case, assuming a setup shown in Figure 11, all the heat from the exhaust is used by the absorption chiller(s) for space cooling. The power from the Rankine cycle (P2) is turned off to maximize the cooling energy supply. If the cooling need drops, P3 can be turned off—mindful that the power supply also drops—which approaches scenario 2. Alternately, P1, P2, and P3 can remain on, which supplies maximum power during a mild summer day.

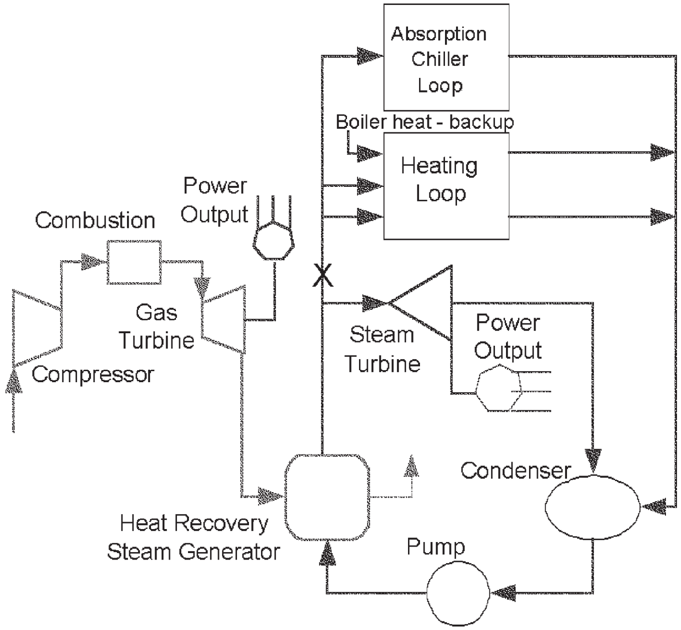

Figure 10. Combined cycle plant with absorption chiller.

Scenario 2 represents a mild summer day with no heating required. Only the base turbine (P1) produces power, without P2 or P3. This leaves sufficient exhaust heat for the absorption chiller. If the cooling need drops, P2 can be turned on, approaching scenario 3.

Scenario 3 represents a mild weather day when minimum cooling is needed, without heating. The base load, P1, runs in a combined-cycle mode with the Rankine cycle, P2. The remaining heat is assumed enough to supply the cooling energy need. The Rankine cycle can be switched off to boost the cooling load if the ambient temperature rises, in the

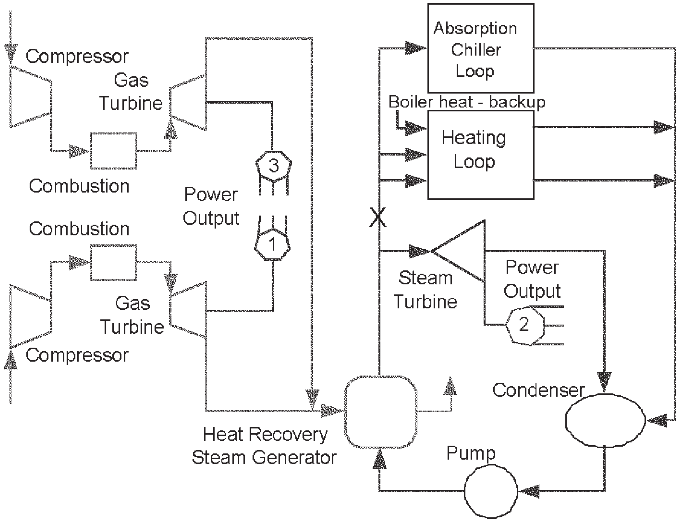

Figure 11. Combined cycle plant with multiple gas turbine engines.

Table 2. Thermal and Power Load Scenarios

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7
P1 (Base)	ON	ON	ON	ON	ON	ON	ON
P2	—	—	ON	ON	ON	—	—
P3	ON	—	—	—	—	—	ON
Heat. Loop	—	—	—	ON	ON	ON	ON
Absorption	ON	ON	ON	ON	—	—	—
Power Level	NO P2	NO P2; NO P3 or, keep P1, P2, P3 ON	NO P3	NO P3	NO P3	NO P3	NO P2

early afternoon for instance. If the temperature is such that no cooling or heating is warranted—a rare or an unlikely scenario—the exhaust from the base load will be bypassed and discharged to the ambient environment.

Scenario 4 represents minimum heating and minimum cooling loads, variant of a mild summer day. Both heating and cooling loops are on. Because the total air conditioning load is assumed to be small, the Rankine cycle is on, sharing the exhaust load and producing power.

Scenario 5 illustrates minimum heat load with no demand for cooling. The combined cycle runs with the Rankine cycle, P2, allowing a bypass to run the heating loop. If the heating need increases, with the power need dropping or remaining about the same, the Rankine cycle can be turned off. Alternatively, P3 can be turned on with P2, which increases the power output but keeps the heat supply about the same.

Scenario 6 represents a need for average heating without cooling. The base load operates without the Rankine cycle, which is bypassed to boost the heating loop. If more power is needed, while the heating load remains about the same, P3 can be turned on with P2.

Scenario 7 represents a very cold winter day. In this case, all heat from exhaust is used for (space) heating. The power output from the Rankine cycle (P2) is bypassed to maximize the heating energy supply. P2 can come online as the heating demand decreases.

These seven scenarios do not account for power load variations, which can be matched to the site load, or maintained slightly above import, to avoid peak charges. This may result in mismatch between heating/cooling demand and supply, forcing some waste heat bypass to the atmosphere. The overall performance will however, still be acceptable. The operating profile of the system is shown in Figure 12.

With site hot water requirements, cooling load, electric-peak demand, annual operating hours, and energy prices, a CCHP system can be sized for the above scenario. Output of the numerical model, and the recommended size, is given in Table 3.

This approach sizes the system for the current campus energy needs, leaving sufficient flexibility for future growth. When the load exceeds the supply, the extra power will be purchased from the utility company. Adding an absorption chiller system requires a substantial upfront capital cost, and fundamental change in the cooling system, including piping modifications. However, it provides more flexibility to cover the cooling load, eliminating the need for chillers and thereby reducing the electric load of the site.

Results of the sizing process are presented without the extensive,

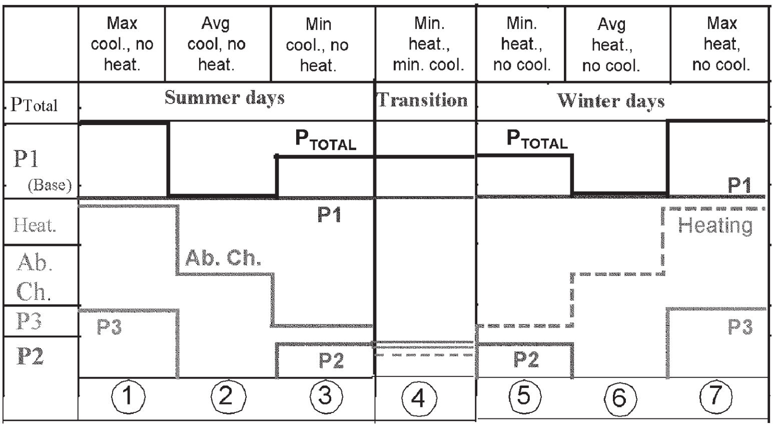

Figure 12. Possible system response to a wide range of thermal load variations (the 7 scenarios)

but fairly simple, mathematical model.

A more economical scenario can be chosen by eliminating the chilled water system from the design and adding a steam turbine instead of the absorption chiller (i.e., combined cycle plant), Table 5. This will eliminate the need for the chilled water piping, trenching and associated equipment. Although the simple payback is longer, this system may better fit the needs of the future campus and produce a better life cycle cost savings.

These conceptual solutions clearly suggest that design of a flexible CHP system requires a thorough feasibility study with in-depth knowledge of the utility profile covering both the power and the thermal aspects. Recent field data seem to suggest that without addressing system flexibility and part-load issues at the design level, a CHP system operation will fall far short of its specifications during most of its operating hours [2, 3]. Establishing such a wide range of operating schedules covering relevant load levels implies that a fair level of control strategy must be integrated into the feasibility study and design stages.

CONCLUSION

In addition to accurately sizing the system, assuring successful system design requires built-in flexibility to achieve acceptable perfor-

Table 4. Suggested system, with 1000 ton absorption chiller.

Operating Hours (95% availability)	8,322
Electricity Production (kWh/yr)	32,539,020
Electricity Savings (offset) ($/yr based on $0.10/kWh)	$3,253,902
Demand Savings ($/yr based on $15.00/kW-month)	$527,850
CHP Gas Usage (therm/yr)	2,864,849
CHP Gas Cost ($/yr based on $0.85/therm)	$2,435,121
Waste heat Recovery Savings ($/yr based on $1.20/therm and/or $0.09/kWh)	$263,926
Estimated Maintenance Costs ($/yr based on 0.01/kWh)	$325,390
Total Estimated Cost Savings ($/yr)	$1,285,166
Self Gen Rebate	$600,000

Table 5. Summary of Results without absorption chiller.

Average Electric Output (kW)	5,610
Operating Hours (95% availability)	8,322
Electricity Production (kWh/yr)	47,328,000
Electricity Savings (offset) ($/yr based on $0.10/kWh)	$4,732,800
Demand Savings ($/yr based on $15.00/kW-month)	$504,900
CHP Gas Usage (therm/yr)	4,314,957
CHP Gas Cost ($/yr based on $0.85/therm)	$3,667,713
Estimated Maintenance Costs ($/yr based on 0.008/kWh)	$378,624
Total Estimated Cost Savings ($/yr)	$1,191,363
Self Gen Rebate	—

mance levels throughout—or at least during most of the operating hours. For this, a thorough knowledge of the site—hourly, daily, and seasonal load profiles—is essential. This load profile can then be used to extract extreme load scenarios and install a flexible system to perform well at all, or most of the load range. Most of the problems of newly-installed CCHP systems—at least in Southern California—seem to suffer from lack of built-in flexibility, even when the systems are well-sized for the design specifications. The recent trend of implementing this valuable technology suggests that there is a gap between incentives and design verifications from the viewpoint of flexibility. Addressing such flexibility issues requires qualified and thorough feasibility studies, incorporating operating conditions to make sure that the system will be useful at part-load, which is so common to manufacturing processes or building loads.

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