PART 1— LOAD PROFILING AND EQUIPMENT SELECTION

Sizing CCHP Systems for Variable and Non-coincident Loads

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ABSTRACT

Because of its superior efficiency and peak load mitigation capabilities, considerable attention has been given recently to combined cooling, heating and power (CCHP). The technology enjoys tax benefits, incentives, accelerated permit processes, etc., at the local, state, and federal levels. One serious challenge to the implementation of CCHP systems is matching and sizing the system to strongly and frequently varying load conditions. Load variation is a serious design matter because the system efficiency drops significantly at part-load. This article presents matching and sizing related challenges of CCHP systems with emphasis on operation-related and weather-driven load factors. Regional data were used to evaluate the success of recent incentive-driven CCHP implementations and evaluate the significance of part-load operation on system performance. Load profiling strategies are developed for equipment sizing and selection to mitigate part-load issues and address system flexibilities.

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

BACKGROUND

Purpose built combined cooling, heating, and power (CCHP) systems have been installed at a variety of end-use facilities since the late 1970s. Some of these sites include factories, colleges and universities, hospitals, military bases, hotels, correctional facilities, and commercial buildings. Application of CCHP systems to such varying end-use facilities results in major differences in system designs and consequently poses serious design challenges.

Because CCHP systems utilize waste heat from power generation for heating or cooling, the overall efficiency can be significantly greater than power generating non-CCHP systems. This has direct and significant impact on emission reduction. In addition, electric transmission and distribution losses are negligible because the power is generated and used locally. CCHP can also help mitigate the impact of electricity price volatility, enhance the reliability of the grid, and alleviate transmission bottlenecks.

Because of natural climatic factors and occupancy schedules, there are relatively few end-use facilities that have the coincident loading and consistent load requirements that can be easily accommodated by traditional power generation systems designed for constant load. Utility tariffs and equipment selection are among the many options that further complicate the sizing and selection process.

Much of the current research relevant to CCHP systems focuses on issues other than the variability and coincidence of site loads. For example, the works of Ashok, Dawson, Dickin, Meckler, Ruan, and Walker [1, 2, 3, 4, 5, and 6] all focus on site specific CCHP system optimization. The research often applies well to individual categories such as industry, university, and hospital settings, but it does not provide a general framework within which the distinct economic and loading characteristics of each facility type can be understood. As a continuing trend, there is still much research pertaining to the performance of specific prime movers, such as gas turbines and fuel cells [7, 8, 9, and 10]. These improvements will benefit any CCHP system in which they are implemented, but any single-platform prime mover research will not be of benefit to developing a cross platform understanding of the economics and loading characteristics of CCHP systems in their entirety. Similarly, there is still a fair amount of ongoing research pertaining to the computer simulation of particular CCHP system or component optimization [7, 11, 12, and 13]. Although such research is valuable, it still does not provide the tools necessary to account for strongly variable and non-coincident load profiles over a range of system architectures.

The other prominent type of research currently involving CCHP systems is related to emissions [14, 15, 16, 17, 18, and 19]. Measuring and reducing the emissions associated with certain prime movers and CCHP systems—such as combined cycle gas turbine plants—is necessary and valuable. However, an increase in successful CCHP system deployments, based on existing technology, would be able to achieve considerable emissions reductions with less research and development. Identifying the barriers to widespread successful deployments and developing strategies to overcome those barriers is essential to realizing the multitude of benefits CCHP systems can offer in terms of economics, emissions, geopolitics, and energy efficiency [20, 21, and 22].

While the cited research into CCHP technology has been ongoing, the state of California has simultaneously been directly aiding the deployment of CCHP systems through the Self Generation Incentive Program (SGIP), with mixed results. The intent of the SGIP is to reflect the Public Utility Regulatory Policies Act (PURPA) of 1978 by promoting the development of distributed generation and cogeneration facilities located at utility customer sites that partially or completely offset their energy needs [23]. As an important part of the program, cogeneration facilities represented nearly 60% of the installed generating capacity of the SGIP at the end of 2005. However, questions have been raised about levels of energy efficiency and useful waste heat recovery being achieved at SGIP-assisted cogeneration facilities. Impact evaluations conducted in 2005 indicated that a number of cogeneration facilities were not achieving the efficiency requirements of the SGIP program, or were idle for a significant period of the year [23, 24].

There has been an effort to articulate several issues associated with system integration and controls as a challenge of CCHP systems [25]. One such aspect addresses systems that provide continuous feedback to operators on actual component and system performance to foster continuous optimization and load balancing. This would facilitate validation of claimed efficiencies and compare the actual performance of the systems to manufacturer's specifications. Control algorithms can also help operators and managers make informed utility related decisions. Based on relevant data, such as knowledge of energy prices, weather conditions, etc., operators can make autonomous decisions on whether to generate power locally or buy from the grid. Thus, control systems are crucial for CCHP success. However, for a control system to be useful, the CCHP system must first offer the necessary degree of flexibility. The topic of this article is this system level flexibility, manifested as a design mismatch between site energy load and system thermal/power output, as a likely result of site load fluctuations. More specifically, this article addresses an effort to increase the understanding of the source of strongly variable or non-coincident electric and thermal loads and their effect on CCHP systems. The ultimate goal of this article is to aid in the successful deployment of future CCHP systems into facilities that experience strongly variable or non-coincident electric and thermal loads.

DATA ACQUISITION

Energy usage and site-specific data were collected via on-site surveys by the Pacific Region CHP Application Center (PRAC). The surveys were performed to investigate the feasibility of installing CCHP systems at sites experiencing strongly variable or non-coincident loading.

Billing data were collected to obtain accurate representation of the total utility costs including taxes and bond charges, to establish maximum electrical demand of the facility, and also to characterize the relative cost differences between electrical power and combustible fuels. As part of a feasibility study, securing the actual utility billing invoices is very important because the utility rate structure documents do not allow the determination of the total cost of energy by including taxes and other associated fees, nor do they establish any usage pattern information specific to the facility under investigation. For this project, information pertinent to the survey (annual utility billing and operational data, engineering drawings, etc.) is collected and analyzed when available. If accurate costs of electricity and fuel are not known, then a relative comparison of the two cannot be accurately known either. This comparison is crucial because it produces a value known as "the spark spread," and is a quick indicator of the economic feasibility of installing a CCHP system.

Engineering drawings and site plans serve to depict geographical points of interest to the project. For example, at one assessed facility, the heat sink for some chiller condensers was a deep well that utilized the thermal mass of water in the well. This geological feature at the site would not have been found on any equipment list but could have proved beneficial if integrated into a CCHP system design. Drawings available with site-specific information, along with the utility billing data and operational details, should be collected either before or during the site assessment.

The data collected during the site assessment are processed and analyzed as the CCHP system feasibility survey. Hourly, weekly, and seasonal electric and thermal load profiles are developed based on the installed equipment, weather data, and personnel interviews are cross-checked with and adjusted to match the annual billing data. These load profiles and site specific factors are the basis on which the engineer selects the equipment that will comprise the optimal CCHP system for that facility.

The process of developing an optimal CCHP system design is framed by energy load profiles, but the final design is also highly dependent on certain overriding factors, such as economics pertaining to the local utility and equipment selection options.

UTILITY ECONOMICS

The economic climate of the local utility is a major factor in developing a successful CCHP system. This is because CCHP systems are typically installed to incur financial benefits and not to satisfy an altruistic desire to reduce energy waste. The capital cost of CCHP equipment, operating cost of purchasing fossil fuel to generate electricity and heat, and associated maintenance costs, must be recovered by the avoided cost of purchasing the heating energy and generated electricity for a CCHP system to be economically viable. The ideal utility rate schedule for a CCHP system is one in which the cost of electric power—both usage and demand—is relatively high, and the cost of fossil fuel is relatively low. If fossil fuel is very expensive or unavailable (as in some rural areas), or if the cost of electric power is very low, CCHP systems are not likely to be economically beneficial. Even if the cost per unit of energy suggests that a CCHP system may be feasible, there are other economic factors that must be considered, which influence the physical design of the system:

i. Exporting electric power to the utility: Some utilities will purchase power from customers who generate excess on-site power. In some cases, the purchase price may be high enough to recover the cost of generation and in others, it may be too low to justify a CCHP system. In such a scenario, the option may only exist to fulfill some legislation. The utility sell-back consideration directly impacts the design considerations of the CCHP system. If it is determined to be acceptable for the owner of the CCHP system installation site to export power to the grid, then the CCHP system may be sized above the base load, for instance for the facility peak power demand, assuming waste heat can be utilized optimally. If it is determined that the owner of the CCHP site would not benefit from exporting power to the grid, then the CCHP system could be designed so that the generation capacity is at, or near, the site base load.

ii. Availability of rebates or incentives that offset the installation cost of a CCHP system: Some states provide incentive funding to be distributed through utilities as part of initiatives to increase the number of CCHP installations. This funding can be distributed based on the type of prime mover in the CCHP system, the type of energy source that ultimately powers the system, the generation capacity of the system, or on other terms. Depending on what criteria the funding is distributed, facility owners may choose to install a certain prime mover, use a certain fuel, or generate at a capacity not closely related to site demand for the sake of maximizing the financial benefit that can be secured from the rebate or incentive programs. So, in some cases, rebates or incentives may influence the choice of one prime mover over another, even when the latter may be theoretically better designed from a thermodynamic standpoint. For example, a solar PV system that includes generous incentives may be installed, although the energy needs of the facility are better met by a CCHP system. Similarly, where incentives are provided for CCHP systems using renewable fuels, a readily available fuel—such as natural gas—may be bypassed and the system designed to operate on a fuel with a less consistent heating value—such as landfill gas—only to secure the incentive funds.

Rebates and incentives may also be awarded on the basis of generation capacity. For example, the California SGIP is currently awarding financial incentives for the installation of CCHP systems with a generation capacity of less than 1 MW. In this situation, the owner of a site with a higher power demand may install a smaller CCHP system that is not optimally matched to site demand to secure the incentive money and improve the return on investment.

These differences in prime mover type—fuel source, generation capacity, and incentive initiatives—directly affect the construction—and therefore the cost—of CCHP systems.

The choice of less common prime movers—such as fuel cells, which are produced by relatively fewer manufacturers—may mean higher initial costs, longer lead-times, and specialty contractors. Alternative fuels could require extra equipment for additional safety measures, or a gas compressor. Sizing the system based on the specified generation capacity limits may require more expensive transformers, or switch gear, and the cost of installing an electrical service line at a voltage differing from the existing site service. These additional costs must be weighed against the benefits of the incentives to the system that will incur them.

iii Utility standby charges: Many utility companies charge the owners of CCHP systems a monthly fee for the assurance that the utility will provide adequate power to the facility in the event that the CCHP system goes off line in an emergency, or for maintenance. In some cases, these fees may be small enough that the system can remain economically viable. In other cases, the fees may be so high that they negatively affect the economics of generating power on site. High standby fees tend to be more common in places where electric and fossil fuel utilities are in competition. Although a site owner may want to install a CCHP system of a certain generation capacity to secure the maximum amount of incentive money, the local utility standby charges may partially or entirely prohibit such an option.

LOAD PROFILE

Once it is determined that a CCHP system is feasible for a particular utility climate, the next consideration is the energy load profile of the site—the temporal variation of site electricity and/or heat. From the energy load profile, decisions can be made about the number of prime movers and CCHP system generation capacity to be installed. To develop the energy load profile that characterizes the energy demands of a site, utility billing data, nameplate information, performance data from large energy-using equipment, and the operational details are required. In general, there are four main possibilities for site energy load variations (Figure 1):

I. Constant power load with constant thermal load
II. Variable power requirement with a constant thermal load
III. Variable thermal load, but constant power load
IV. Variable power and thermal loads

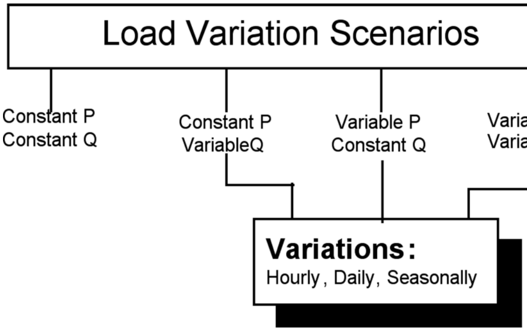

Figure 1. Load variation scenarios

The constant electric/thermal load scenario poses no design challenges, and the system can be selected to satisfy the load with the greatest financial benefit while maintaining the site balance of energy use. For example, at a site where electricity is more expensive than natural gas, a system may be sized with prejudice to maximize power generation. The other load variation possibilities pose serious design challenges, which must be plotted and addressed adequately.

The second energy load profile is the case in which the site demand for electricity and heat varies hourly, but not seasonally. The hourly variation can be used as an approximation for sites that operate the same equipment on the same schedule throughout the year in areas where the weather does not greatly affect energy use. An example could be a manufacturing plant in southern California.

In a non-coincident loading profile, the demand for electricity and heat varies hourly—not seasonally, and the demand for the different forms of energy occurs at different times. This can be a site that requires heat and power at different times throughout the day and is relatively unaffected by seasonal weather patterns. An example would be a hotel in Hawaii that must supply a relatively large amount of heat, in the form of hot water for showers in the early morning and evening, and a large amount of electric power to drive electric chillers, during the later part of the morning and throughout the afternoon.

The case of seasonal variation can be used as an approximation for sites that operate during certain hours of the day throughout the year and face wide swings in occupancy, such as a university in northern California, and sites that experience weather that necessitates different amounts of heating in some seasons and cooling in others. In fall and spring, when the climate is more temperate and occupancy is high, the load profile may vary throughout the day, but the site may use more outside air ventilation to alleviate any heating or cooling spikes in the load profile. In winter, when occupancy is still high and heating is required, the electric load profile may appear similar to fall and spring but the heating load profile may be markedly higher to account for the increased space heating required to maintain zone temperatures. In summer, when occupancy is a fraction of the other seasons, and the need for cooling is high, the heating load profile may appear similar to that of fall and spring, but the electric load profile may be characterized by steep plateaus that occur during peak hours as a result of the demand of electric chillers. The magnitude of the electric power plateau may, however, be greater or less than the magnitude during other seasons because of the decreased occupancy in summer.

A very common situation in many applications occurs when the power supply can be considered fairly constant—leaving variable thermal load. In such a case, the following seven thermal load possibilities of three main categories can be investigated [26]:

A) No heating load, only cooling-load, which represents summer cases with:
    i. Maximum cooling, all chillers operating
    ii. Average cooling, chillers operating partially
    iii. Minimum cooling, chillers operating at low part-load

B) Small cooling and heating, seasonal intermediates:
    iv. Parallel cooling and heating required at very low load levels

C) No cooling load, only heating load—winter cases with:
    v. Minimum heating
    vi. Average heating
    vii. Maximum heating

An ideal system would run near maximum efficiency during all these load scenarios, with minimum heat loss to the ambient environment. One way to mitigate thermal load variations is to use absorption chillers for cooling. This use of waste heat significantly increases capital cost and often renders the system economically unfeasible. The choice of cooling, which requires absorption chiller, and heating, alternating from the same recovered heat source, offers a very flexible system, assuming the power load remains constant and the CCHP system is sized optimally.

EQUIPMENT SELECTION

Once the economics of the utility are determined, and the load profile is established, equipment related factors should be considered:

i. The first step in selecting equipment for a CCHP system is to check local laws and building codes to be certain that both the type of equipment and installation location of the equipment are permissible. (In California, for example, it is not legal to use diesel fuel for primary power.)
ii. The price of equipment can exceed the cost of similar equipment in similar projects used in the economic estimate, for a number of reasons. Some newer technologies—such as fuel cells—have been available with large discounts, as part of a rush by the manufacturer to have the equipment installed and demonstrated to be operating in the field. As the technology matures, those early discounts may have been repealed until the cost of equipment reached its estimated market value. In other components of a CCHP system—such as heat exchangers—the price of equipment is closely tied to the material cost of the equipment. As prices on commodity metals increased, the cost of this type of equipment also increased so that the cost of projects constructed years ago may no longer be applicable today.
iii. Certain components that may form part of a CCHP system—such as a steam turbine—can have lead times of approximately one year. If a site owner is determined to secure a utility incentive by completing construction of the system within a certain date, then the lead time on equipment is critical. Rushing to design and

install a system, only to learn later that equipment critical to the design cannot be procured by the necessary date, can cause the system owner to issue a change order or miss the deadline for the incentive. Both of those consequences could ruin the economics of the CHP system.

iv. Auxiliary equipment considerations are also a concern. The output of the CCHP system may not match the site utility service, and thus the possibility of installing an inverter, transformer, switch gear, and/or power conditioning equipment (depending on the prime mover), must be considered. This is especially true if the system owner plans to export power to the utility grid.

v. The proposed construction site must be checked to insure that the seismic protection measures are feasible. For example, a proposal to install a CCHP system on the roof of a building may not be permitted if concrete equipment pads are required by the building code, or if the fire code prohibits fuel storage tanks or transportation lines from being rigidly mounted at that height. Failure to consider these important factors may result in the project being delayed or canceled after a substantial investment in the design process.

CONCLUSION

CCHP is a very promising technology that offers partial solutions to outstanding energy related problems and also contributes to pollution reduction. Sizing the system for a targeted load—thermal or power—often leaves the system significantly under-utilized for a large portion of the year when the load varies, shifting to off-design range from either thermal or power, or both sides.

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.

The case studies included in this article may not ideally typify the conditions under which CCHP systems with traditional operating strategies are struggling; however, they provide a glimpse at the level of complexity and issues that should be accounted for in determining feasibility of CCHP systems. The strategies developed here also merit ongoing research as a means to correct existing problems and adjust the design considerations for future installations.

It may be possible to integrate a CCHP system into a site—such as a hotel—that experiences hourly load variations and non-coincident loading, by implementing a prime mover alternation strategy in addition to the 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 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. Part 2 of this article will build on these results to address operational strategies to improve part-load efficiencies.

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