Economic Sizing and Dispatch of Central Energy Plant Equipment at the Navy Medical Center, San Diego

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ABSTRACT

The Navy operates a central energy plant providing cooling, heating, and electric power to their hospital in San Diego. With aging equipment, uncertain loads, and volatile energy prices, the Navy was facing critical issues regarding replacement equipment sizing and dispatch of all equipment at their facility. The Pacific Northwest National Laboratory* developed a spreadsheet model to determine the economic optimum size of new turbine generators and absorption chillers, and the economic dispatch of the entire central energy plant. This article describes the analytical approach taken for the study, with an emphasis on the optimization problems and strategies. Specific results for the Navy hospital are also presented.

INTRODUCTION

At the request of the Navy Public Works Center, San Diego (NPWCSD; hereinafter referred to as the Navy) and the U.S. Department of Energy's (DOE) Federal Energy Management Program (FEMP), the Pacific Northwest National Laboratory (PNNL) evaluated the economic sizing and dispatch of central energy plant (CEP) equipment at the Navy

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Medical Center, San Diego (NMCSD; hereinafter referred to as the hospital).

The CEP provides electricity, steam, and chilled water to the hospital. Major existing equipment includes:

- three 800-kW turbine generators with heat recovery steam generators (HRSGs)
- one 800-ton single stage absorption chiller
- two 800-ton electric centrifugal chillers
- one 1200-ton electric centrifugal chiller
- three 25,000 lb/hr boilers
- four 1200-ton cooling towers.

The CEP also has three 600-kW diesel generators devoted to life-critical loads that are only dispatched when other electric power sources fail.

Except for the cooling towers and 1200-ton electric centrifugal chiller, the other equipment listed above was installed in 1985. At the time this study was conducted (2001), the Navy planned on replacing the remaining 1985 vintage equipment, except for the boilers. The three turbine generator and heat recovery steam generator sets were to be replaced with similar equipment. The 800-ton absorption and electric centrifugal chillers were to be replaced with two double-effect absorption chillers. Thus, the immediate issue for the Navy was to determine the optimum sizes for the new equipment. Of equal importance was the optimum equipment dispatch for the renovated central energy plant.

ANALYTICAL CONSIDERATIONS

Equipment sizing and dispatch decisions are often complicated at combined cooling, heating, and power plants and especially so at the Navy hospital CEP. Electricity can either be self-generated and/or purchased from the grid. Steam can be provided from the boilers and/or the gas turbine HRSGs. Chilled water can be generated from absorption and/or electric chillers. The self-generation decision affects the amount of steam available from the HRSGs. The marginal costs of HRSG and boiler steam are different, causing the marginal cost of operating the absorption chillers to vary. The hospital's demand for electricity, steam, and chilled water vary with the season, the day of the week, and the hour of the day. Finally, grid electricity and natural gas prices have been volatile in recent years, especially in California. Suffice it to say that the equipment sizing and dispatch decisions for the Navy hospital CEP warranted a structured analytical approach.

The overall approach taken was to first define the hospital cooling, electric, and steam loads. Cost and performance characteristics were then developed for existing and prospective CEP equipment. Although uncertainty exists with these variables, the degree of uncertainty was judged to be low enough to model these variables as deterministic values. In contrast, the uncertainty in future energy prices was treated by examining multiple gas and electricity price scenarios. Optimum equipment sizing and dispatch were then determined simultaneously for each of the energy prices scenarios. Each of these principle elements of the analysis are described in more detail below.

HOSPITAL LOADS

A logical first step for any assessment of a central energy plant is to define the loads to be served. For the Navy hospital, this includes electricity, chilled water, and steam loads. As in many endeavors, timing is very important when characterizing building energy loads served by a combined cooling, heating, and power facility. Annual load data alone are practically useless. Monthly or daily load data are better, but hourly load data or at least estimates of such are necessary for an accurate assessment. Otherwise, for example, it would be easy to mistakenly assume that all steam produced by the HRSGs could be used and/or that adequate steam would be available from the HRSGs. With two supply options each for electricity, steam, and chilled water, the development of hourly load profiles for each of these three utilities was a prerequisite to further analysis.

Cooling Load

The Navy provided PNNL with hourly cooling load data for 22 days in 1998, as well as monthly cooling load data for the same year. The hourly data covered both weekdays and weekends from several different months throughout the year. Examination of the data indicated no significant difference in the load profiles for any day within a single month, i.e., no significant difference based on the day of the week. In addition, month-to-month variation could best be described as a "rising or falling tide," i.e., the hour-to-hour and minimum-to-maximum variation was nearly constant. The load data were developed by first calculating an average annual daily load profile (i.e., the average across all days for each hour of the day). Each average annual hourly load was adjusted upward or downward by a constant amount until the resulting daily load profile matched the monthly totals when multiplied by the number of days in each month.

Electric Load

The Navy provided PNNL with 15-minute electric load data for purchased and generated electricity from mid-July, 2000 through mid-July, 2001. These data were aggregated to average hourly loads for weekdays and weekends for each month of the year to be consistent with available cooling and steam load data. However, the Navy data did not distinguish between CEP and hospital loads, so these had to be estimated.

Development of the hospital electric load required estimating and subtracting power used by the chillers, condenser water pumps, and cooling towers. The total cooling load was first segregated into portions served by the existing absorption and electric centrifugal chillers. Per Navy advice, the absorption chiller was presumed preferentially dispatched. When the cooling load required multiple chillers, the load was presumed split evenly among the operating chillers. Absorption chiller operation, including condenser water pumps and cooling tower fans, was assumed to consume 0.14 kW/ton. Electric centrifugal chiller operation, including condenser water pumps and cooling tower fans, was assumed to consume 0.77 kW/ton. Chilled water pumping power was assumed to be the same per ton regardless of chiller type and was implicitly left in the "hospital" electric load. Finally, the resulting hospital electric loads derived from the above procedure were adjusted to match the monthly electric loads (less estimated chiller related load) for 1998.

Steam Load

The Navy provided monthly steam production data from the HRSGs and boilers. Absorption chiller steam demand was subtracted from the Navy data to estimate the hospital steam load. Absorption chiller steam demand was estimated from the absorption cooling loads described above, with the existing single-stage absorption chiller assumed to consume 19.5 lb/hr of steam per ton of cooling. No data describing the diurnal variation of hospital steam demand were available, but the Navy believed such variation to be small.

EQUIPMENT COST AND PERFORMANCE

Determination of optimum equipment sizing and dispatch also required characterizing the cost and performance of existing and prospective new equipment. Purchase, installation, and annual operating and maintenance (O&M) costs for gas turbines with HRSGs were based on data developed by Onsite Sycom Energy Corporation (1). Gas turbine and HRSG performance data were acquired from Solar Turbines' web site. Absorption chiller purchase, installation, and annual O&M costs were based on a combination of data from Trane (personal communication), the U.S. Department of Energy (2), and PNNL (3). Absorption chiller performance assumptions were based on data from the U.S. Department of Energy (2) and ESource (4). Auxiliary chiller electricity consumption assumptions were based on data in Colen (5). Finally, electric chiller and boiler performance were based on factory specifications and reported performance by Navy personnel. Specific assumptions are listed in the Appendix.

ENERGY PRICES AND ECONOMICS

Decisions regarding equipment sizing and dispatch are usually driven by energy prices. The so-called "spark-spread" between natural gas and grid electricity prices is often the primary motivation for self-generation of electricity. The same price spread also affects preferences between the use of absorption or electric chillers directly or indirectly because of the availability of HRSG steam as a by-product from electricity generation.

The following baseline electricity and natural gas price assumptions were provided by the Navy:

On-peak electricity: $0.09256/kWh
Off-peak electricity: $0.05456/kWh
Natural gas: $4.84/MMBtu

Mid-peak electricity was assumed priced at the average of on-peak and off-peak rates or \$0.07356/kWh. The occurrence of on-peak, off-peak, and mid-peak periods was set per the San Diego Gas and Electric Schedule AL-TOU General Service tariff.

Energy prices have been volatile nationwide in recent years, but particularly so in California. Thus, the usual importance of investigating alternative energy price scenarios was magnified. Per advice from the Navy, alternative electricity prices were set equal to 2/3, 4/3, and 5/3 of the baseline rates; alternative natural gas prices were set equal to 2/3 and 4/3 of the baseline rates. The four electricity and three natural gas price assumptions were combined to form 12 different energy price scenarios. Natural gas prices were assumed to escalate at 2.19%/year and electricity at 2.38%/year. Again, these assumptions were provided by the Navy.

Project economic life was assumed to be 20 years, with project financing provided to the Navy by an Energy Service Company at 10%/year*. O&M costs were assumed to escalate at 2.7% per year. Economic optimum was based on achieving the minimum present value of future CEP capital, fuel, and O&M costs over a 20-year period.

EQUIPMENT SIZING AND DISPATCH

CEP operation was simulated for each hour of representative mid-week and weekend days for each month of the year. Thus, 576 hours (24 hours × 2 days × 12 months) were simulated to represent an entire year. Hourly inputs were the hospital cooling, electric, and steam loads; electricity and natural gas prices; and dry-bulb temperature†. Hourly outputs were electricity purchase, electricity generation, steam production from HRSGs and boilers, and chilled water production from absorption and electric chillers.

The optimal equipment dispatch was determined for each hour by selecting the minimum operating cost option from the alternative dispatch strategies presented in Table 1. The optimum gas turbine and absorption chiller sizes were simultaneously evaluated over the allowable size range for each. The simultaneous optimization was conducted

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*Discount rate and energy/O&M escalation rates in nominal terms, i.e., including inflation.

†Dry-bulb temperature was included in the model of gas turbine performance.

Table 1. Alternative Dispatch Strategies[*]

Strategy Code	*Turbine Strategy*	*Chiller Strategy*
A	Minimize use—run only when boiler capacity is insufficient to supply required steam demand	ABS[†] chillers are used first. VC[§] chillers are only used when ABS capacity is insufficient to meet load or when HRSG and boilers cannot provide enough steam.
B	Minimize use—run only when boiler capacity is insufficient to supply required steam demand	VC chillers are used first. ABS chillers are only used when VC capacity is insufficient to meet load.
C	Turbine runs to the extent possible to meet the hospital and chiller electrical requirements	ABS chillers are used first. VC chillers are only used when ABS capacity is insufficient to meet load. Boilers are fired to run ABS units if necessary.
C′	Turbine runs to the extent possible to meet the hospital and chiller electrical requirements	ABS chillers are used first. VC chillers are only used when ABS capacity is insufficient to meet load or when steam from HRSG is not sufficient for ABS units to meet load. Turbine output is increased to meet chill requirements using both ABS and VC units.

(*Continued*)

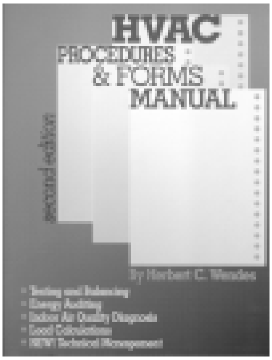
Table 1. Alternative Dispatch Strategies* (***Continued***)

Strategy Code	*Turbine Strategy*	*Chiller Strategy*
D	Turbine runs to the extent possible to meet the hospital and chiller electrical requirements	VC chillers are used first. ABS chillers are only used when VC capacity is insufficient to meet load. Boilers run to supply steam to ABS units if output from HRSG is insufficient.
E′	Turbine runs to the extent possible to meet the hospital and chiller steam requirements. However, when HRSGs cannot meet steam requirements, turbine output is increased to provide steam and electricity for chillers.	ABS chillers are used first. VC chillers are only used when ABS capacity is insufficient to meet load or when steam from HRSG is not sufficient for ABS units to meet load. Turbine output is increased to meet chill requirements using both ABS and VC units.
F′	Turbine runs to the extent possible to meet the hospital and chiller steam requirements. However, when HRSGs cannot meet steam requirements, turbine output is increased to provide steam and electricity for chillers.	VC chillers are used first. ABS chillers are only used when VC capacity is insufficient to meet load. Turbine output is increased to produce steam for ABS units when required and additional output is sold to the grid.

*Additional strategies incorporating electricity sales were included in the spreadsheet but excluded here in keeping with Navy guidance.

†Absorption.

§Vapor compression.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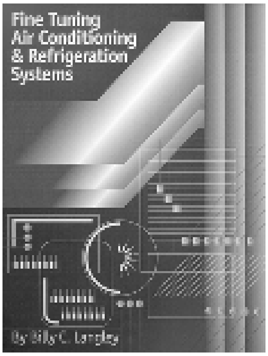

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using the Solver tool in Microsoft (Excel, which uses a non-linear optimization code) (6).

Gas turbine capacity was constrained to a minimum of three 1250-kW units, corresponding to the minimum capacity requirement to meet critical hospital services. The maximum capacity was limited to the peak hospital demand because the Navy was not interested in the possibility of selling electricity to the grid. Absorption chiller capacity was constrained to a minimum of two 750-ton units which, when combined with the 1200-ton electric centrifugal chiller, would meet the peak cooling load. Larger absorption chillers were considered up to the point where absorption chillers could meet the peak cooling load without operating the electric chiller. The optimal dispatch strategies for the 12 energy price scenarios are shown in Table 2. The optimal gas turbine and absorption chiller sizes are shown in Table 3.

The optimal gas turbine capacity was found to be the minimum constraint (three units @ 1250 kW each) at the baseline energy price scenario and for other scenarios with a relatively small difference between electricity and natural gas prices (i.e., the "spark-spread"). As the spark-spread increases, the optimal gas turbine capacity increases above the minimum constraint, but is always less than 2 MW for each of three units, for all energy price scenarios investigated.

The optimal absorption chiller capacity was also found to be near the minimum constraint (two units @ 750 tons each) at the baseline energy price scenario. In contrast to the optimal gas turbine capacity, the optimal absorption chiller capacity was found to track more with electricity price than the spark-spread. The highest electricity prices investigated pushed the optimal absorption chiller unit size up to about 900 tons. Although higher (grid) electricity prices favor absorption chiller operation, self-generation of electricity keeps electrical centrifugal chillers competitive in these scenarios.

CONCLUSIONS

Combined cooling, heating, and power plants present myriad design and operating options that must be carefully evaluated to deter-

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*The baseline energy price assumptions specified by the Navy are identified by bold print in Tables 2 and 3.

Table 2. Optimal Dispatch Strategies*

Natural Gas, $/MMBtu	**On-Peak Elec, $/kWh**	**Mid-Peak Elec, $/kWh**	**Off-Peak Elec, $/kWh**	**Optimal Dispatch Strategy Code**
3.23	0.062	0.049	0.036	C' all hours
4.84	0.062	0.049	0.036	B off-peak; C on-peak E' winter mid-peak; B summer mid-peak
6.45	0.062	0.049	0.036	B all hours
3.23	0.093	0.074	0.055	C' all hours
4.84	**0.093**	**0.074**	**0.055**	**C' all hours**
6.45	0.093	0.074	0.055	B off-peak; C' all other
3.23	0.123	0.098	0.073	C' all hours
4.84	0.123	0.098	0.073	C' all hours
6.45	0.123	0.098	0.073	C' all hours
3.23	0.154	0.123	0.091	C' all hours
4.84	0.154	0.123	0.091	C' all hours
6.45	0.154	0.123	0.091	C' all hours

Table 3. Economic Optimal Gas Turbine and Absorption Chiller Capacities

Natural Gas, $/MMBtu	**On-Peak Elec, $/kWh**	**Mid-Peak Elec, $/kWh**	**Off-Peak Elec, $/kWh**	**Optimal Gas Turbine Unit Capacity, kW (1 of 3)**	**Optimal Abs Chiller Unit Capacity, Tons (1 of 2)**	**20-Year System Present Value, $M**
3.23	0.062	0.049	0.036	1250	750	$30.78
4.84	0.062	0.049	0.036	1250	750	$35.27
6.45	0.062	0.049	0.036	1250	750	$37.91
3.23	0.093	0.074	0.055	1486	774	$33.09
4.84	**0.093**	**0.074**	**0.055**	**1250**	**771**	**$41.31**
6.45	0.093	0.074	0.055	1250	750	$46.50
3.23	0.123	0.098	0.073	1708	829	$33.76
4.84	0.123	0.098	0.073	1494	852	$43.56
6.45	0.123	0.098	0.073	1250	845	$51.82
3.23	0.154	0.123	0.091	1772	852	$34.09
4.84	0.154	0.123	0.091	1680	902	$44.24
6.45	0.154	0.123	0.091	1499	909	$54.00

mine the optimum choices. Even when building loads and equipment characteristics can be relatively well defined, volatile energy prices make it difficult to determine optimum equipment sizes and will likely change the optimum dispatch strategy even when equipment sizes are fixed. Recognition of system constraints will minimize the number and/or range of choices that must be investigated. Nevertheless, special analytical techniques may be required to adequately address the complexity and uncertainty. This paper has illustrated the combined use of multiple scenarios (for energy price uncertainty), "exhaustive" search (for equipment dispatch options), and non-linear optimization (for simultaneously examining equipment dispatch and sizing options) techniques to identify the optimum equipment sizing and dispatch at the Navy's hospital in San Diego.

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Daryl Brown and **Jim Dirks** are both staff engineers at the Pacific Northwest National Laboratory, where each has approximately 20 years of experience conducting evaluations of energy technologies. Mr. Brown has a degree in chemical engineering from Oregon State University, while Mr. Dirks has a degree in electrical engineering from the University of Washington. Both have MBA degrees from the University of Washington and are Certified Energy Managers. Their prior work has resulted in more than 100 publications in the energy field.

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APPENDIX

Equipment Cost and Performance

Gas Turbine

Installed Cost, $ = 7,477.7*(kW)^0.7756

Annual O&M, $ = 36,518.9*EXP(0.00007031*kW) + 0.0046*kWh

ISO Full Load Higher Heating Value Heat Rate, Btu/kWh = 29,477 – 1954.9*LN(kW)

Part Load Heat Rate Correction Factor = 0.9851*(kW/ISO kW)^-0.327

Ambient Temperature Heat Rate Correction Factor = 0.965544 + 0.000584*T(F) if T<=59

Ambient Temperature Heat Rate Correction Factor = 0.910320 + 0.00152*T(F) if T>59

Ambient Temperature Maximum Power Output Correction Factor = 1.23836 – 0.00404*T(F)

Heat Recovery Steam Generator Capacity, lb/hr = 5623.74 * EXP(0.0003202*kW)

Absorption Chiller

Installed Cost, $ = 1,819.4*(tons)^0.8452

Annual O&M, $ = 20*(tons)

Steam Consumption = 10 lb/ton-hr

Auxiliary Electricity Consumption = 0.14 kW/ton

(Includes electricity for absorption chiller pumps, condenser water pumps, and cooling tower fans)

Electric Centrifugal Chiller

No new centrifugal chillers, so no centrifugal chiller capital cost.

All cases include existing 1200-ton electric centrifugal chiller. Annual O&M presumed proportional to capacity, hence same for all cases and ignored.

Chiller Electricity Consumption = 0.54 kW/ton

Auxiliary Electricity Consumption = 0.09 kW/ton

(Includes electricity for condenser water pumps, and cooling tower fans)

Boiler

No new boilers, so no boiler capital cost.

All cases include existing three 25,000 lb/hr boilers. Annual O&M presumed proportional to capacity, hence same for all cases and ignored.

Efficiency = 80%