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CHP SELF ANALYSIS

Steve Fischer
Oak Ridge National Laboratory
P.O. Box 2008, MS-6070
Oak Ridge, TN 37831-6070
United States of America
fischersk@ornl.gov

Jason Glazer
GARD Analytics
1028 Busse Highway
Park Ridge, IL 60068-1802
United States of America
jglazer@gard.com

ABSTRACT

Two techniques are described for preliminary screening of facilities to determine potential cost and energy savings from implementing combined cooling, heating, and power. The first technique can be performed with a simple hand-held calculator and employs average costs for equipment, power, and fuel. The second technique employs a simulation tool run on a desktop computer. It draws upon extensive databases for equipment cost and performance, utility rates, and calculated building electrical and thermal loads.

NOMENCLATURE

ADD CHP	Accelerated Development and Deployment of Cooling, Heating and Power systems
BCHP	buildings cooling, heating, and power
CCHP	combined cooling, heating and power
CHP	cooling, heating, and power
$\overline{C}_e$	average cost of electricity ($/kWh)
$\overline{C}_{export}$	average cost of electricity exported to the grid ($/kWh)
$\overline{C}_{fuel}$	average cost of fuel for distributed generation ($/MBtu, multiply by 0.948 for $/GJ)
$C_{standby}$	utility standby charge for backup power at DG sites ($/kW/year)
$\overline{C}_{O\&M}$	average non-fuel O&M costs for power generation ($/kWh)
DG	distributed generation
gCOP	efficiency of indirect-fired absorption chiller (e.g. 0.7 for single-effect, 1.2 for double-effect)
H	operating time (h/y)
HVAC	heating, ventilating, and air conditioning
IES	integrated energy systems
kW_e	kilowatt, electricity
kWh	kilowatt-hour
kWth	kilowatt, thermal
MBtu	million Btu (multiply by 1.055 for GJ)
O&M	operating and maintenance
P	installed cost of CHP equipment ($/kW)
$\dot{Q}_e$	electrical load or demand (kW_e)
$\dot{Q}_{th}$	thermal load (kW_{th})
ton	refrigeration ton (12,000 Btu/h, 3.52 kW)
$\alpha_{heat\ rate}$	heat rate or fuel requirement for DG equipment (Btu/kWh)
$\beta_{useable\ heat}$	fraction of recovered waste heat that can be used to offset purchases of heating fuel
β_1	fraction of recovered waste heat used to offset purchases of natural gas or fuel oil
β_2	fraction of recovered waste heat used to offset purchases of electricity for cooling
$\delta_{misc\ losses}$	miscellaneous thermal losses from DG equipment (%)
ε_{hrb}	effectiveness of heat recovery equipment (%)
γ	fraction of generated electricity used on site
η_{boiler}	efficiency of existing heating equipment (%)
$\eta_{chiller}$	efficiency of electric chiller (kW/ton, divide by 3.52 for kW_e / kW_{th})

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INTRODUCTION

The rolling power blackouts across California during the winter of 2000-2001, skyrocketing energy costs tied to prices of natural gas during that same period, and fears about "energy security" after the September 2001 terrorist attacks have all contributed to a frenzy of interest in distributed generation (DG) of electricity and on site power generation with heat recovery. While DG will allow some sites to maintain greater control over their electrical supply, combining heat recovery with localized power generation has greater potential for reducing overall energy consumption and reducing costs. Naturally the Department of Energy is interested in these integrated technologies as steps toward achieving national goals for reductions in energy use and carbon emissions.

A multitude of similar acronyms, such as CHP, CCHP, and BCHP, are used to describe these systems, but they all mean essentially the same thing; recovering waste heat in the form of steam or hot water from the production of electricity in order to satisfy a concurrent thermal load. The heat can be used for domestic hot water, space heating or dehumidification, powering an indirect-fired absorption chiller, or charging a thermal storage tank. The overlying concept is that operating costs, energy use, and carbon emissions are all reduced because a greater percentage of the primary energy is used to meet building or process needs.

The Department of Energy is involved in combined heat and power through many different avenues. One office is sponsoring work to develop more efficient IC engines and gas turbines to drive electric generators, to develop "modular packaged systems" for cogeneration of heat, power, and chilled water, and to develop computer software to aid managers in determining if there is economic potential for CHP for their site. A second program within DOE, works out of a separate office to provide federal energy managers with information on the types of equipment available for CHP, equipment cost and performance characteristics, and on avenues for financing CHP projects. This program is also providing a free screening analysis for federal sites through its Advanced Development and Deployment of Cooling, Heating, and Power (ADD CHP) project. This paper addresses first the processes developed by the authors for the ADD CHP screening analysis and second the CHP screening software being developed.

CHP SAVINGS FACTOR

Any manager considering CHP is faced with deciding when it is worthwhile to incur very high investments in equipment (and training) to reduce operating costs. Generally the manager is also facing this choice without a lot of information or guidance on how to make decisions. The authors developed a relatively straightforward algorithm that incorporates nine parameters including the average cost of electricity and fuel at the site and the value of recovered heat to estimate the net savings from operating a CHP plant. The terms are defined in the nomenclature section of this paper. Basically the value of combined heat and power is determined from the avoided cost of purchasing electricity, minus the cost of producing power, plus the value of recovered heat. The "CHP savings factor" or $\Delta\overline{C}_{CHP}$ estimates savings from the CHP system in $/kWh of electricity generated and is computed using the following equation:

$$\Delta\overline{C}_{CHP} = \gamma\cdot\overline{C}_e + (1-\gamma)\cdot\overline{C}_{export} - \overline{C}_{O\&M} - \frac{C_{standby}}{8760} - \frac{\alpha_{heat\ rate}\cdot\overline{C}_{fuel}}{10^6}\times\left[1-\frac{\beta_{useable\ heat}}{\eta_{boiler}}\cdot\left(1-\frac{3413}{\alpha_{heat\ rate}}-\delta_{misc\ losses}\right)\cdot\varepsilon_{hrb}\right] \quad (1)$$

using 8760 hours per year, 10^6 Btu/MBtu, and 3413 Btu/kWh.

The last term on the right of the equation represents the avoided cost of fuel required to produce steam or hot water equivalent to the energy recovered from the exhaust and engine jacket of the generating equipment. Technically, for a CHP system using an absorption chiller or desiccant dehumidifier this term should be split into sections for the avoided cost of fuel for heating loads and avoided cost of electricity cooling loads. This is shown in Eq. (2):

$$\Delta\overline{C}_{CHP} = \gamma\cdot\overline{C}_e + (1-\gamma)\cdot\overline{C}_{export} - \overline{C}_{O\&M} - \frac{C_{standby}}{8760} - \frac{\alpha_{heat\ rate}\cdot\overline{C}_{fuel}}{10^6}\times\left[1-\frac{\beta_1}{\eta_{boiler}}\cdot\left(1-\frac{3413}{\alpha_{heat\ rate}}-\delta_{misc\ losses}\right)\cdot\varepsilon_{hrb}\right] - \frac{\alpha_{heat\ rate}\cdot\overline{C}_{fuel}}{10^6}\times\left[1-\frac{\beta_2\cdot gCOP\cdot\eta_{chiller}\cdot\overline{C}_e}{12000\cdot\overline{C}_{fuel}}\cdot\left(1-\frac{3413}{\alpha_{heat\ rate}}-\delta_{misc\ losses}\right)\cdot\varepsilon_{hrb}\right] \quad (2)$$

where β_1 and β_2 are the fractions of recoverable waste heat used for heating and cooling loads, respectively, gCOP and $\eta_{chiller}$ are the efficiencies of the absorption and electric chillers, and there are 12,000 Btu per ton of cooling.

The calculation thus becomes a process of gathering data, deciding the type of generator to use, making a rough guess for the generating capacity, and filling in some estimated parameters.

Collecting Data Utility bills provide information on monthly consumption, demand, and cost data (consumption and demand charges) and can be used to compute annual consumption, the average cost of electricity and fuel, the average electric demand, and with a conversion of units the ratio of average thermal load to the average electric demand. The average and peak electric demands help in estimating a reasonable generating capacity for a CHP system at the site while the ratio of thermal to electric load helps in selecting the type of generator to use.

Utility rate schedules or riders for on-site generation can be used to identify any of a variety of charges to customers installing on site generation. These include standby charges to cover their cost of guaranteeing backup capacity for scheduled and unscheduled outages and exit fees to recover stranded costs of generation or distribution equipment. These may be hard to locate

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and a preliminary evaluation may be performed assuming a best case ($C_{standby}$=\$0.00) and a reasonable guess ($C_{standby}$=\$25.00) to determine if further effort is worth while.

Engine- and turbine-generator manufacturers literature can provide approximate heat rates, average O&M costs, exhaust air temperatures (can be used to estimate heat recovery heat exchanger effectiveness), and installed costs. Some representative values are listed in Table 1 that can be used in preliminary analyses to determine if there is sufficient merit to warrant searching for more precise information. Boiler manufacturer literature or nameplate information can be used to determine fuel consumption, capacity, and boiler efficiency.

Finally, chiller and boiler room logs can be used to estimate thermal loads and the fraction of waste heat that may be applied to steam, hot water, or chilled water loads.

Selecting Equipment There are a number of different types of equipment that can be used for on-site generation of electricity; (1) natural gas fired IC-engine generators, (2) combustion gas turbines, (3) microturbines, (4) fuel cells, (5) photovoltaic cells, and (6) wind generators. Only IC-engine and gas turbine driven generators are discussed in this paper, although the analysis could be stretched to include microturbines and fuel cells (most microturbines recover and use exhaust heat internally to boost their generating efficiency resulting in reduced exhaust temperature and quantities of heat to recover for other uses, fuel cells remain very expensive with high costs for periodic stack replacement, while suitable for on-site generation photovoltaic cells and wind generators do not have application in CHP systems). The ratio of thermal to electric load can be used as a rough guide in choosing between IC-engine and combustion gas turbine generators [Q_{th}/Q_e <1 for IC-engine generators, between 1 and 2 for gas turbines (Smith et al., 2001)].

Sizing Equipment The purpose of selecting a generator capacity at this point is to get approximate values for installed cost, efficiency or heat rate, operating and maintenance costs, and thermal capacity. Most, but not all, CHP installations are designed for a high number of annual operating hours (peak shaving systems are much less common). The average electric demand, peak electric demand, and average thermal load can be used to make an educated guess on generator size using the information for thermal capacity in Table 1.

Computing $\Delta\overline{C}_{CHP}$ At this point the calculation is simply a matter of substituting values into the equation for the CHP savings factor. Consider an example where:

- annual electric costs are \$1,790,000,
- power consumption is 19,890,000 kWh per year,
- natural gas cost \$1,290,000/year,
- and gas consumption is 956,000 therms or 95,600 MBu (100,900 GJ).

Then:

- the average cost of electricity is \$0.09/kWh
- the cost of fuel is \$13.50/MBtu (\$12.80/GJ)
- average electric demand is close to 2300 kW,
- the average thermal load is about 10.9 MBu/h (3200 kW_{th}),
- and the ratio of average thermal load to average electric demand is about 1.4.

The average thermal to electric ratio is reasonable for a gas turbine-generator; the average electric demand and thermal loads (2300 kW and 10.9 MBu/h, 3200 kWth) could be a good match for a 1,000 kW gas turbine from Table 1. Assume for argument's sake that:

$$\Delta\overline{C}_{CHP} = \$0.090 - \$0.010 - \frac{\$25.00}{8760} - \frac{14{,}025 \cdot \$13.50}{10^6} \times \left[1 - \frac{1.00}{0.72} \cdot \left(1 - \frac{3413}{14{,}025} - 0.02\right) \cdot 0.68\right] = \$0.0195 / \text{kWh} \quad (3)$$

- the local utility charges \$25/kW/year to guarantee backup power if the system is down for maintenance or repairs,
- the boiler at the site has an annual efficiency of 72%,
- that radiation and other heat losses from DG equipment are 2%,
- and that the waste heat recovery boiler has an effectiveness of 0.68.

Then using Eq. (1) for the sake of simplicity,

PAYBACK

Simple payback can serve as a reasonable parameter for screening purposes to decide whether or not there is sufficient potential to follow up with a more rigorous analysis. Simple payback can be given by Eq. (4):

$$N = \frac{P}{H \cdot \Delta\overline{C}_{CHP}} \quad (4)$$

where P is the installed cost of the equipment (\$/kW of electrical capacity) and H is the annual operating hours for the CHP plant (hours/year). A best case scenario could be checked by computing the payback using 24 hours per day, 365 days per year for CHP operation, but the analyses for the ADD CHP program generally subtracted two weeks of scheduled and unscheduled downtime for gas turbines and three weeks per year for IC-engine systems. For this example then, the simple payback is 9.1 years if 100% of the recoverable waste heat can be used. The payback increases logarithmically as the waste heat use decreases toward 85% since the CHP savings factor decreases to zero. An estimated nine year payback is probably good enough to warrant further analysis using refined estimates for waste heat use, boiler efficiency, and utility standby charges.

Figure 1 was created using the assumptions and equations above and shows diagonal lines of constant payback for this example; the costs of electricity and natural gas on the horizontal and vertical axis. The leftmost diagonal line corresponds to the demarcation point where the CHP savings factor is zero and there would be an infinite payback period. The vertical line on the graph represents the payback periods for the 1200 kW system in this example for various assumptions on ability to use waste heat. At 100% usage of recovered heat (corresponding to the marker at the bottom of this line), the payback is nine years, payback increases as the amount of waste heat that can be used decreases. It crosses the zero savings / infinite payback line at about 85% waste heat use. The point corresponding to 75% use of waste heat is

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above the infinite payback line (or "no payback") because the cost of operation exceeds the avoided cost of electricity and value of recovered heat.

Many sites experienced unusually high gas and heating oil costs during 2000 and 2001, and it may be of interest to consider CHP potential if rates in the future are lower. In Fig. 1, if the long term cost of natural gas drops from the $13.50/MBtu ($12.80/GJ) used in the calculations to $7.50/MBtu ($7.10/GJ), then the payback line slides downward to the $7.50/MBtu ($7.10/GJ) level on the vertical axis and shows a simple payback of four years if 100% of the recoverable waste heat can be used effectively.

The staff responsible for the ADD CHP program offer to work with federal facilities to perform calculations similar to these to ascertain the economic potential of CHP systems at their sites. Participating sites provide information on fuel and electrical use and costs, peak electrical demand, and estimates on the capacity and age of heating and cooling equipment. In return they receive estimated simple payback results and recommendations for follow-up evaluations as appropriate.

CHP SCREENING TOOL

The CHP savings factor and simple payback calculations presented above provide some guidance on whether or not it is worthwhile to investigate CHP for a site. They are limited in value because they are using the average cost of fuel and electricity, "typical" costs for equipment, and practically no information about the site thermal and electrical loads. The Department of Energy recognized that there was a need for an easy to use computer program for a more rigorous screening of building sites considering CHP and contracted with thermal modeling specialists in Chicago to develop the CHP Screening Tool to serve this purpose. This program draws upon data from many sources:

- TMY2 weather data for 239 U.S. cities,
- commercial gas and electric utility rates for 160 U.S. cities,
- performance and cost database for HVAC equipment,
- performance and cost database for power generating equipment, and
- a database of DOE2.1e building design parameters for computing electric and thermal loads.

A straightforward graphical user interface allows the user to select heating, ventilation, air conditioning (HVAC) and generating equipment from drop down lists, to edit data for equipment costs, utility rates, or performance, and to type in different building design parameters. The program runs the building energy program DOE2.1e so that it is transparent to the user and then returns a multitude of calculated results for energy costs, energy consumption, peak loads, etc. Computing concurrent thermal and electrical loads, whether through DOE2 or other software, gets over the hurdle of not knowing how much of the recoverable waste heat can be used effectively, removing a major uncertainty in the earlier analysis. Output from the CHP Screening Tool includes tabular and graphical displays of monthly and annual energy consumption and costs and economic factors including project cost, simple payback, and internal rate of return.

Three of the "internal" databases form a critical component of the CHP Screening Tool. Experts in utility tariffs assembled an extensive array of commercial rate schedules for the major cities and metropolitan areas in the U.S. so that program users can make preliminary calculations using rates for a nearby city without putting a tremendous amount of effort into deciphering their own rate schedules. As users progress from "interested in CHP" to "seriously interested" they can copy existing utility tariffs in the database and edit them to reflect their actual rate structure. The HVAC equipment database includes manufacturer's data across broad ranges of capacity for:

- single- and double-effect steam or hot water fired absorption chillers,
- single- and double-effect direct-fired absorption chillers,
- engine-driven chillers,
- centrifugal, reciprocating, and screw electric chillers,
- rooftop air conditioners and heat pumps,
- desiccant dehumidification systems,
- gas-fired boilers and water heaters,
- cooling towers, and
- both ice and chilled water thermal storage.

Users can construct a base case with traditional electric and gas equipment and up to 25 alternative scenarios including on site power generation with heat recovery and thermally activated chillers and dehumidifiers. The power equipment database consists of cost and performance information, including waste heat recovery, for 160 current and future models of IC engine (5 kW to 5.8 MW), gas turbine (1210 kW to 25 MW), and microturbine driven generators (28 to 500 kW) and fuel cells (200 kW to 25 MW). As with the HVAC equipment database, selecting power equipment is as simple as pointing and clicking with a computer mouse.

While the CHP Screening Tool puts a lot of information at the user's fingertips, it relies on effort and judgement on the user's part to select and match equipment, building, and utility assumptions for the CHP calculations. While there is some internal scaling of equipment sizes to building loads, it does not automatically configure the CHP system or perform extensive checks to make sure that the user configured system makes sense. The user needs to work with the building specification to ensure that the computed loads will be a reasonable approximation of those for his own building, to study different cases to select a good match of generating equipment and end uses for waste heat (absorption chillers, desiccant dehumidifiers, steam heaters), and to make sure that the utility rates employed are applicable to his facility. The ADD CHP type of analysis helps to determine if this necessary investment of effort is worthwhile. Work with the CHP Screening Tool can then be performed to decide if it is worthwhile to invest hard money in outside consultants and specialists for a rigorous analysis, design, and construction.

CONCLUSION

Combined cooling, heating, and power can be an effective approach for many building owners to control their energy costs while reducing dependence on the electric grid and contributing toward federal energy and environmental goals. Combined cooling, heating, and power for other building owners can be a tremendous investment of time and resources with little or no return. The tools and algorithms presented in this paper can assist people in determining which group they are in; is it worth their while to invest time and effort into learning more about CHP or are they best served by remaining focused on their primary operations. Performing either type of self-analysis helps the building owner or operator understand what CHP design engineers are doing if and when they are called in. Forethought and careful targeting of resources will help focus on CHP projects with strong potential and

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lead to achieving national energy and environmental goals effectively.

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Table 1. CHP Parameters

Generator Prime Mover	Installed Cost ($ / kW)	$\alpha_{\text{heat rate}}$ Btu / kWh (kJ / kWh)	Thermal Capacity Btu / h (MJ / h)	$\overline{C}_{O\&M}$ ($ / kWh)
IC-Engine				
a. 1,000 kW	$1,250	12,000 (12,600)	3,000,000 (3,000)	$0.0125
b. 5,000 kW	$900	10,250 (10,810)	15,000,000 (16,000)	$0.0120
c. 10,000 kW	$800	8,500 (9,000)	31,000,000 (33,000)	$0.0110
Gas Turbine				
a. 1,000 kW	$1,500	14,025 (14,795)	8,000,000 (8,400)	$0.0100
b. 5,000 kW	$1,250	11,225 (11,840)	26,000,000 (27,000)	$0.0060
c. 10,000 kW	$1,000	10,525 (11,090)	49,000,000 (52,000)	$0.0025

Sources: Fairbanks Morse; Orlando, 1996; Smith et al., 2001; Solar Turbines.

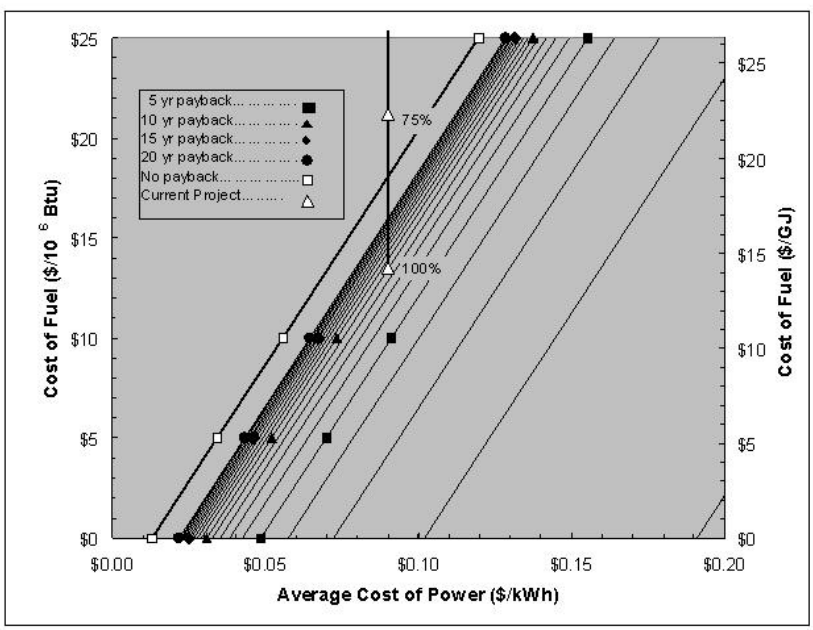

Fig. 1. Simple payback chart for CHP system.

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