CHP – the "Ugly Duckling" of Energy Efficiency

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Abstract

Combined heat and power (CHP) systems offer utility customers significant electricity-savings and emissions-reduction opportunities, but for a combination of reasons are seldom included as an eligible measure in electric DSM programs:[1]

- Electric utilities generally object to all measures that feature fuel switching, which CHP systems exemplify, and are inclined to discourage the installation of measures that involve electricity generation because this generation competes with its own generation (in the case of vertically integrated utilities), or where restructuring occurred and the utility is owned by a holding company, the latter has another subsidiary that owns and operates generating units.
- Customer-sited generation complicates maintenance of the distribution grid.
- The systems involve fuel combustion, and thus there is not a direct correlation between electricity savings and emissions reductions (there is a net reduction, but it is much less than the amount produced by energy efficiency programs).

This paper presents the methodology for determining savings potential of large-scale CHP initiatives and presents results for two of them, one that is state-wide (in Maryland) one that is one that is region-wide (Pacific Northwest). It also discusses the potential barriers to the success of programs that feature CHP systems, and describes some ways to overcome these barriers.

Introduction

The history of power conversion can be traced back some 4000 years to small installations of water wheels doing some form of mechanical work, and primitive rotating helical tubes to lift water from a river or lake to a field in which grain is grown. Crude forms of windmills appeared during a later period. While the combustion of biomass to raise steam first appeared in ancient Egypt, the first practical uses of steam power began during the early 19th century. Steam power and water power were used to generate electricity at manufacturing plants beginning in the late 19th century. With steam power plants, it was a simple step to recover and use the heat remaining in the steam exiting the steam engine or turbine, and thus combined heat and power (CHP) or "cogeneration" was born. It soon became an established technology for manufacturing plants and large institutions such as universities and hospitals where large quantities of both electricity and steam or hot water were needed. Many such applications have persisted throughout the 20th Century and into the 21st, although the number of such installations decreased as equipment wore out and many owners decided not to replace the plants because the price of electricity sold by utilities had continually dropped as utilities built ever-larger and more efficient centralized power plants.

Three important points to be recognized are:

1. Power generation pre-dates the utility industry and was originally done on-site at or close to the point where power is needed. Many of these early customer-sited power plants were CHP systems.

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[1] They have been included in gas-utility DSM programs, however, but only on a relatively limited basis.

2. CHP is highly desirable because it is highly efficient. In properly designed plants, more than 75 percent of the annual energy contained in the fuel can be used – 20 percent to 50 percent as electricity and the balance as heat (which can be used to produce chilled water and air-condition buildings). The high efficiency typically results in lower pollutant emissions than would occur with traditional generating and fuel-to-heat systems.
3. CHP cannot eliminate the need for the utility grid, but it can reduce the need to build more power plants and expand the grid, while reducing the cost of energy to end-users.

Although the role of CHP in the nation's electricity-supply infrastructure has dropped over the past 100 years, CHP has not disappeared. Paper mills, wood-products plants, oil refineries, some chemical plants, and waste-water treatment plants all have the need for both electricity and steam, and have combustible wastes that can be used as fuel. CHP installations are "standard practice" at these facilities. Some universities and large hospitals continue to operate on-site CHP plants. These CHP systems are economic because they serve electrical and thermal loads that are large in all months of the year, which means the CHP operates at a high efficiency on an annual basis and cost savings are achieved.

The past 25 years have seen the development of small-scale CHP units, with electrical outputs in the 50-kW to 5-MW range. These units are not as economic as large CHP plants, but they can achieve a 4- to 5-year payback period in some applications because:

- Efficient and low-cost diesel and gasoline engines—and combustion turbines—have been produced in large quantities for transportation applications (automobiles, trains, ships, aircraft) during the last half of the 20th Century, and it is a simple matter to couple these low-cost prime movers to generators.
- The systems are physically compact and quiet, are factory assembled, can operate automatically without human actions, except for routine maintenance.
- It is easy to convert the prime movers to be fueled by natural gas, propane, or a variety of alternative liquid or gaseous fuels, including biogas (methane from landfills or waste-water treatment plants) or "green" fuels containing ethanol or vegetable (e.g., soy) oil.
- Retail electricity prices have risen and are expected to continue to rise.
- Emission levels are low and satisfy all but the most stringent air-quality requirements.
- The Public Utilities Regulatory Policies Act of 1978 (PURPA) required utilities to (1) permit the installation and operation of CHP units that satisfy specified efficiency criteria, and (2) purchase some or all of the electricity they generate, paying the utility's "avoided cost," calculated as prescribed by a cognizant regulatory agency.
- The thermal (steam or hot-water) output can drive adsorption-cycle air-conditioning, which means a large fraction of the thermal energy produced annually can be used.

It is important to note that CHP installations are not intended to eliminate the purchase of utility-generated electricity; only to reduce these purchases. The basic idea is that the utility grid will provide "back-up power" at times when the CHP system is down for maintenance, or whenever there is no need for the thermal output from the plant. The price that utilities charge for "standby" back-up service is one of the most contentious remaining issues associated with CHP. There are a wide variety of ways that a "fair" charge can be calculated, and the different parties have widely different concepts concerning which method is most appropriate.

Although several thousand small-scale CHP systems have been installed around the nation over a 20-year period, this represents only a miniscule portion of the potential market. Therefore, it must be said that small-scale CHP has failed to gain traction in the energy marketplace. The reasons for this failure include:

- Opposition by some electric utilities, who often imposed high “back-up” charges and sometimes offered customers a special low retail rate to persuade them to abandon a planned CHP installation. In all cases, utilities had to approve the “electric interface”
- Difficulties in obtaining permits for systems (before emissions-control equipment was developed).
- The usual “hassle factors” for commercial customers (e.g., skepticism about savings claims, difficulties obtaining financing, lack of familiarity with the equipment, need for multiple permits).
- Early equipment failures because customers did not arrange for periodic preventative maintenance. (As a result, most of the small-scale units that were installed have been abandoned and sold as scrap.)

Although historically virtually all CHP installations have been in non-residential facilities, over the past 15 years there have been several large-scale test programs of residential CHP systems in Europe, Japan, and Australia (Paparone 2009). During the past few years, interest in residential CHP has migrated to the U.S. (Bance 2009). National Grid has been conducting a pilot program in Massachusetts over the past few years (Halfpenny 2008). It should be noted that all fuel cell power units are CHP systems, and more than 500 large (e.g., 200-kW and 250-kW) units have been installed and successfully operated. A great deal of the nation’s current fuel cell research and development efforts (both federally funded and privately funded) is focused on residential applications of fuel-cell CHP units.

Policy Implications

Potential energy savings—both electricity and fuels—and greenhouse gas (GHG) emission savings achieved with a well executed CHP program are significant. The nation cannot afford to ignore the energy efficiency resource provided by expanded use of efficient CHP systems. This point is reinforced by a just-published ORNL report (Shipley et al. 2009), which in the Executive Summary (p.3) states:

> “Combined heat and power (CHP) solutions represent a proven and effective near-term energy option to help the Unites States enhance energy efficiency, ensure environmental quality, promote economic growth, and foster a robust energy infrastructure. Using CHP today, the United States already avoids more than 1.9 Quadrillion British thermal units (Quads) of fuel consumption and 248 million metric tons of carbon dioxide (CO_2) emissions annually compared to the traditional separate production of electricity and thermal energy.
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> “… It is not a single technology but a but a group of technologies that can use a variety of fuels to provide reliable electricity or mechanical power, and thermal energy at a factory, university campus, hospital, or commercial building—wherever the power is needed.
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> “… The generating capacity of the more than 3,300 US CHP sites now stands at 85 gigawatts (GW) —almost 9 percent of US total capacity.”
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> “… CHP is one of the few options in the portfolio of energy alternatives that combines environmental effectiveness with economic viability and improved competitiveness.”

Methodology

This paper describes the results of detailed analyses of CHP potential shown in two studies:

1. Work performed for Bonneville Power Authority by the authors of this paper and their colleagues at TechPlan Associates and ADM Associates to develop an estimate of CHP potential in the commercial and industrial sectors in the Pacific Northwest region as a function of the price paid for excess electricity that was sold to the grid (TechPlan Associates 1989).

2. Work performed by a team assembled by ACEEE to examine the application of a wide variety of energy efficiency measures in Maryland, which included an estimate of CHP potential in the commercial and industrial sectors performed by team members employed by Energy and Environmental Analysts (EEA).[2] (ACEEE 2008).

TechPlan Associates Study for BPA

The geographic area served by BPA's power generation and transmission network extends over portions of eight states: all of Washington, Oregon, and Idaho, Western Montana, and small portions of Northern California, Nevada, Utah, and Western Wyoming. More than a hundred public and private utilities operate in the region and are served by BPA, although most also receive power from other sources as well. Because BPA is responsible for distributing low-cost hydropower produced at a network of federally owned dams, the price of its electricity is the lowest in the region. To support the region's economy, BPA is authorized to sell excess electricity to a few dozen large manufacturing plants.

During the mid-1980s the Bonneville Power Administration (BPA) undertook a series of investigations of new technologies that could be used for power generation. One such technology was cogeneration. TechPlan was a member of a team that responded to an RFP issued by BPA, and was selected to conduct the study. The following paragraphs describe how this study was performed. It should be noted, however, that the same general process is used for all technology-assessment studies, and indeed was used for the CHP-in-Maryland study that is also described in this paper – but with different datafiles and a different computer program.

Segmentation and Characterization of Host Facilities. The scope of the CHP potential study covered not only the full BPA service area, but the balance of Montana as well. The first step was to segment the region geographically, based on 10 retail electricity price levels and three climate representations (climate affects electric loads an, as noted previously, load and electricity price affect CHP economics). The result was 23 subregions, each similar electricity prices and similar climate. The second step was to develop a representation of potential host facilities where CHP system might be installed. A review of the facility counts in the Washington and Oregon, as shown in the U.S. Census Bureau's *County Business Patterns* datafiles, led to the decision to consider 25 facility types (11 industrial (e.g., food, wood products, paper,[3] chemical, fabricated metal product) and 14 commercial (e.g., office, retail, restaurant, hospital, school, university, nursing home, waste-water treatment[4]). Since "size matters" because of economies of scale effects (as noted previously), each of the 25 facility types ("FacTypes") were represented by four size categories. The result was an overall segmentation of 2,300 potential host facility (HF) entities (4 sizes of 25 types in 23 subregions). The number of actual facilities ("FacNum") represented by each of the 2,300 HF entities was then developed by analyzing the *County Business Patterns* datafiles.

The final step in characterizing the HF entities was to develop:

1) Electrical and thermal load profiles for a "representative facility" for each of the 25 FacTypes that was assumed to be located in the mildest climate,
2) Scale-factor multipliers to adjust the load profiles so as to represent the four size categories, and

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[2] EEA was subsequently acquired by ICF, Inc.

[3] Wood products and paper plants are especially attractive host facilities because (1) they have large and steady reasonably thermal and electrical loads, and (2) they have wood-waste that can be used as a low-cost fuel, and paper plants produce "black liquor" as a waste product that can be used as a free fuel in a CHP system

[4] Waste-water treatment facilities are also especially attractive host facilities because (1) they have large and steady thermal and electrical loads, and (2) they produce methane gas as a waste product that can be used as a free fuel that is mixed with natural gas in the ratio of three parts methane to one part natural gas.

3) Climate factors to adjust the load profiles for the two more severe climate zones.

Because each different type of CHP system can produce a thermal energy supply at one or more specific temperature levels (including a chilled-water level of 40ºF that can be used for air-conditioning), up to three different thermal load profiles were developed for each FacType. The electric load profile was for the baseline (pre-CHP) condition. This profile was adjusted to remove the load of the electric chiller or other HVAC system that did not operate when a chilled-water supply was delivered by a CHP system. Fortunately, TechPlan's partner in this study, ADM Associates, had recently completed a study for BPA that involved characterizing commercial and industrial facility loads. These data were used by ADM to define the needed load profiles, scale-factor multipliers, and climate factors.

Today, with modern super-fast computers, load profiles might be represented on an hourly basis. At the time when this study began (1987), desk-top computers were about 500 times slower, and hence a relatively crude representation of the time dimension had to be employed: four time segments in each of three seasons. However, considering the large uncertainty in knowing what the profiles actually are, because of differences among the thousands of actual facilities represented by each HF entity, this representation is believed to be a reasonable representation of reality in that it does capture the time-varying nature of the electrical and thermal loads.

Cogeneration System Representation. The basic method employed was to sequentially evaluate the technical and economic performance of a large number of candidate CHP systems in each of the 2,300 HF entities. In this study 22 different CHP systems were considered, ranging from 30-kW engine-driven units to 300,000-kW steam turbines and combined-cycle systems. Each type had thermal output at one or more specific temperature levels, and each could be applied at various capacity levels ("sizes") over a specific range of capacity values. Installed cost of the system varied inversely with capacity, with a different relationship specified for each CHP system type. Fuel oil and natural gas were a common fuel for all CHP systems, but the price varied inversely with system capacity. Low-cost fuel was assumed to be available at wood products, paper, and waste-water treatment facilities.

As part of the assessment involving a given candidate CHP system and one of the 2,300 HF entities, three or four different operating modes were investigated: electric load following and thermal load following, excess sell-to-grid, sell-all-to grid. (The last two only when CHP capacity was 500-kW or more.) The result is that a large number of variations involving capacity level and operating mode could be—and often were—assessed for each combination of CHP system type and HP entity.

Cogeneration Regional Forecasting Model (CRFM). In parallel with the segmentation and HF characterization activities described above, the CRFM computer program was developed and programmed in FORTRAN. As noted above, the general procedure is to sequentially assess the technical feasibility and economic performance of variations of each of 22 CHP systems in each of the 2,300 HF entities, considering the price paid for any electricity sold to the grid as the primary variable. Technical feasibility included size compatibility and the ability to satisfy at least one thermal load, and this served to quickly eliminate certain combinations (e.g., small-capacity systems applied in large HF entities, and vice-versa).

If the performance for a given HF entity and CHP system combination satisfied a specified economic internal-rate-of-return (IRR) "hurdle rate" criterion and savings-percentage criterion, the results were temporarily stored while other operating modes, capacities, and CHP system types are assessed. The CHP capacity that satisfied the dual criteria (IRR and percentage savings) and produced the highest IRR was the one assumed to be installed. Total installed MW capacity and MWh/yr savings were then calculated by multiplying the results obtained by FacNum, adjusting for known CHP systems that are already installed in the HF entity being considered, and multiplying by a "market factor" that reduced the result as a function of IRR to reflect the fact that low IRR installations are unlikely to be completed because the owner will be poorly motivated to overcome barriers such as difficulty in obtaining financing and making time to evaluate bids and retain contractors. The results were stored in the final results array and the entire assessment process is then repeated for the next HF entity.[5]

When the assessments are completed for all 2,300 HF entities, the entire process is repeated for a point in time five years later. FacNum values were adjusted to reflect assumed growth rates in HF populations. CHP system prices and fuel and electricity prices were all escalated for these runs.

ACEEE CHP Potential Assessment for Maryland

As the following description shows, the basic approach and process for developing the technical, economic, and market potentials of CHP in the state of Maryland are quite similar to the approach in the BPA study.

- *Identify existing CHP in the state.* There are 18 operating CHP plants in Maryland, totaling 829 MW of capacity. This existing CHP capacity is deducted from any identified technical potential.
- *Identify applications where CHP provides a reasonable fit to the electric and thermal needs of the user.* Target applications were identified based on reviewing the electric and thermal energy (heating and cooling) consumption data for various building types and industrial facilities. Data sources include the DOE EIA Commercial Buildings Energy Consumption Survey (CBECS), the DOE Manufacturing Energy Consumption Survey (MECS) and various market summaries developed by DOE, Gas Technology Institute (GRI), and the American Gas Association. Existing CHP installations in the commercial/institutional and industrial sectors were also reviewed to understand the required provide for CHP applications and to identify target applications.
- *Quantify the number and size distribution of target applications.* Once applications that could technically support CHP were identified, the iMarket, Inc. MarketPlace Database and the Major Industrial Plant Database (MIPD) from IHI were utilized to identify potential CHP sites by SIC code or application, and location (county). The MarketPlace Database is based on the Dun and Bradstreet financial lists and includes information on economic activity (8 digit SIC), location (metropolitan area, county, electric utility service area, state) and size (employees) for commercial, institutional and industrial facilities. In addition, for select SICs limited energy consumption information (electric and gas consumption, electric and gas expenditures) is provided based on data from Wharton Econometric Forecasting (WEFA). The MarketPlace Database and MIPD were used to identify the number of facilities in target CHP applications and to group them into size categories based on average electric demand.
- *Develop performance factors for a wide assortment of CHP system types.* The critical performance factor is thermal output for each category of thermal output (characterized by temperature level, including chilled-water) as a function of electrical output.
- *Estimate CHP potential in terms of MW capacity.* Total CHP potential was calculated for each target application based on the number of target facilities in each size category. It was assumed that the CHP system would be sized to meet the average site electric demand for the target applications unless thermal loads (heating and cooling) limited electric capacity.
- *Estimate the growth of new facilities in the target market sectors.* The technical potential included economic projections for growth through 2020 by target market sectors.

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[5] At the time when the first complete CRFM runs were made, in 1988, 8 hours were needed to complete an assessment for one electricity sell-back price, so runs were done overnight. (Obviously, this also meant program debugging also was a long, tedious process!) Fortunately great advances were made in desk-top computers over the next six months and before long a complete run could be done in 30 minutes. In 2009, the required time would be less than a minute, but the CRFM program no longer exists.

- *Develop estimates of electricity and fuel prices in each utility service territory.* EIA data were used for retail electricity prices (varies with customer-facility size and load factor). Natural gas prices were based on Henry Hub wellhead price forecast and the delivered price including transport from Henry Hub.
- *Develop estimates of CHP system costs and performance parameters.* The team members from EEA who performed the CHP study have a long history of performing similar studies, and have an extensive database of CHP costs and performance data.
- *Develop parameters for a market penetration analysis.* The EEA CHP Mark analysis model estimates cumulative CHP market penetration in 5-year increments (2010, 2015 and 2020). The economic potential is calculated by using a probability of installation as a function of payback period curve that was developed by surveying decision-makers at potential host facilities.

Results

TechPlan Associates Study for BPA

Table 1 shows the market potential results as a function of sell-to-the-grid electricity price. Note that the potential increases exponentially with price

Table 1. Market Potential as a Function of Sell-to-Grid Electricity Price (1989$)

Sell-to-Grid Price ($/kWh)	Market Potential (AMW*)
$0.020	186
$0.025	255
$0.030	410
$0.035	824
$0.040	1,560
$0.045	4,600
$0.050	7,510
$0.055	12,600
$0.060	20,000

* AMW = Average megawatts: A unit of electrical energy used by Pacific Northwest utilities (1.00 AMW = 1.00 MW present for 8,760 hours per year, or 1.00 AMW = 8,760 MWh/yr)

ACEEE CHP Potential Assessment for Maryland

The total CHP technical potential by 2020 is estimated to be about 4,000 MW. The economic and market potentials are:

Financial Incentive ($/kW)	Economic Potential	Market Potential
$ 0	295 MW	97 MW
$600	778 MW	224 MW

With the incentive, total electricity savings are estimated to be about 850 million kWh/yr greater in 2020 than they would be without the incentive.

Conclusions

CHP potentials are a strong function of either electricity "sell-to-grid" price or a financial incentive that is offered as part of an energy efficiency program. In the current national situation, where it is the policy of the federal government as well as of many state government agencies to promote energy efficiency as a means for reducing GHG emissions and minimize electricity price increases, as well as other goals (e.g., improve air quality and economic competitiveness, reduce the need for new transmission lines and power distribution network upgrades), CHP should no longer be excluded from lists of eligible measures.

References

[ACEEE 2008] American Council for an Energy-Efficient Economy. 2009. *Energy Efficiency: The First Fuel for a Clean Energy Future – Resources for Meeting Maryland's Electricity Needs.* Report E082. Washington, D.C. February.

Bance, P. 2009. "Residential-Scale Fuel Cell CHP a Better Match for Domestic Loads." *Cogeneration and On-Site Power Production*, 2009 (3). May / June.

Halfpenny, T. 2008. *Micro Combined Heat and Power – An Analysis of the Climate Energy Freewatt™ System*. KeySpan Energy Delivery paper presented at the 18th National Energy Services Conference. Clearwater Beach, Florida. January.

Paparone, M. 2009. "Micro-CHP Comes to North America." *Cogeneration and On-Site Power Production.* 2009 (3). May / June.

Shipley et al. 2008. *Combined Heat and Power ─ Effective Energy Solutions for a Sustainable Future*. ORNL/TM-2008/224. Oak Ridge, Tenn. Oak Ridge National Laboratory. December 1

TechPlan Associates. Assessment of Commercial and Industrial Cogeneration Potential in the Pacific Northwest. report prepared for Bonneville Power Administration by TechPlan Associates, Bala Cynwyd, Penn., March 1989.