Part 1 of 2

The CHP Space: A Basic Model

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"Essentially, all models are wrong, but some are useful"
—*George E.P. Box*

ABSTRACT

A fundamental graph-and-math based methodology to develop engineering-economic models of cogeneration systems is reported here. This report has two parts. In Part 1, the CHP Demand and Supply plane is developed; Technology T and System S lines are introduced; and several design and evaluation considerations are discussed. Part 2 (forthcoming) will describe the states of nature of an interconnected CHP system and will prescribe a set of linear equations for the economic modeling of Combined-Heat-and-Power plants. As a whole, the underlying models will be instrumental to build further cogeneration system analysis, design, evaluation and optimization models and programs. Future articles will report further developments.

Keywords: CHP Space, Cogeneration, Combined-Heat and Power, Design, Graph Model

INTRODUCTION

Cogeneration systems are highly efficient energy conversion plants which supply power (electrical or mechanical) and thermal energy (heating or cooling) for a district (e.g. a town), a facility (e.g. a hospital) or a process (e.g. a food dryer). Such "total energy" plants are also called combined heat and power or CHP systems. CHP systems can achieve as much as 80% to 90% total-system energy efficiency. See Figure 2.

Cogeneration can achieve very significant savings in primary fossil fuels and a much lower environmental impact than conventional or separate power and boiler/chiller plants. When compared to a conventional way of generating heat and power (Fig. 1), well integrated CHP systems (Fig. 3) can achieve as high as 40% energy savings in primary energy (fuel). This research focuses on the development of basic graph-and-math model to represent a CHP system performance economics with respect to on-site electrical and thermal loads in the X-Y plane. The resulting models shall be used to develop further and more complex CHP system design models in future articles.

A true CHP system is intended primarily to serve the heat and power needs of the host facility or process. However, as shown in Figure 3, a cogeneration plant can (1) buy back-up power from the utility grid and (2) sell excess power (micro-grid) or heat (district heating/cooling) to nearby users, (3) power to the utility; or through the utility grid, (4) to a dedicated customer base (wheeling).

Purpose, Organization and Approach

An integrated, graphical approach is presented here for the analysis, design and evaluation of cogeneration systems. The underlying graph-and-math approach is the knowledge base and foundation upon which further analysis, design and optimization work can be developed. Thus, more sophisticated models can be derived by using the CHP Space model given here.

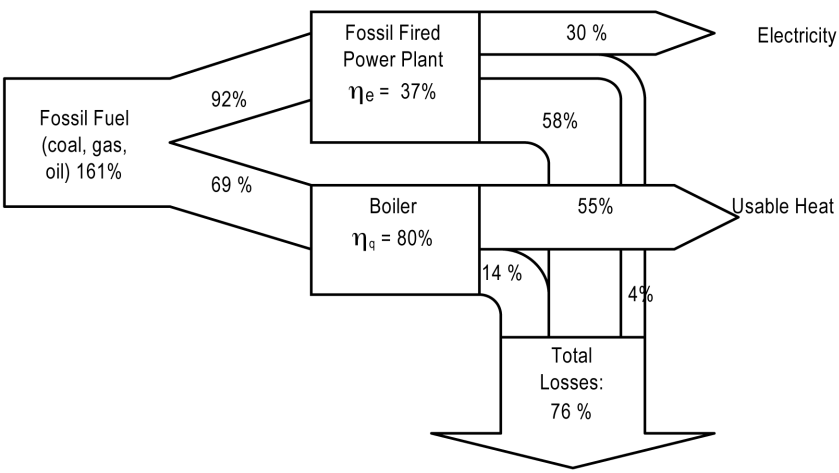

Figure 1. Separate generation of heat and power in boiler and conventional power plant

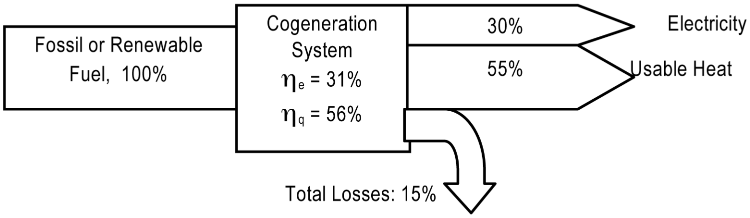

Figure 2. Cogeneration of heat and power.

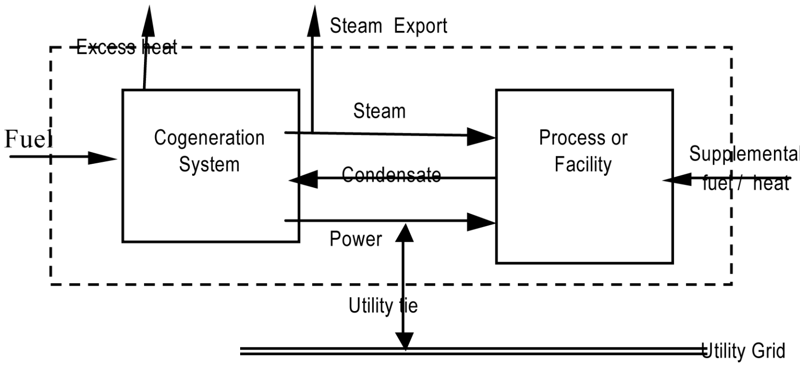

Figure 3. Integration of cogeneration system and process/facility.

The report is organized as follows. In this article (Part 1 of 2) the CHP Supply and Demand Space is established. Next, the technology and system curves are defined. Then, some CHP design and evaluation considerations are discussed. In the following article (Part 2 of 2), the economic-design model is derived. Finally, a graph and math representation of linear CHP systems in the X-Y plane is developed. Generally speaking, such a representation is made of lines and their corresponding equations, which will help formulate optimization math models.

As stated by G.E.P. Box, models are inaccurate abstractions of real systems and processes. Thus, modeling implies focusing on the most significant design variables, while neglecting less significant variables. Understanding what variables to include in and which to exclude from a model, requires cogeneration know how, sensitivity analysis and experience with actual systems. For example, in the US, one significant factor is the impact of the Public Utilities and Regulatory Act of 1978 or PURPA regulations on the sizing cogeneration plants connected to the utility grid.

CHP DEMAND AND SUPPLY: A MODEL ON THE X-Y PLANTE

In this section, the cogeneration supply (system size or capacity) and demand (on-site CHP load) problem is formulated in the Cartesian space. In the most idealized case, the CHP system capacity equals the on-site CHP demand; hence no power import or export occurs. However, this case is only possible if the CHP plant and the host process are well integrated. Such a base case will be the basis upon which enhancements will be added later to model complex cases with acceptable fidelity, but without unnecessary complexity.

Let's define the CHP space (Figure 4) where the abscissa *P* represents the *power* demand and supply and the ordinate *H* represents the *heat* demand and supply. Note the conventional generation scenario of separate heat and power supply (shown schematically in Figure 1) is represented in Figure 4 by one horizontal and one vertical line:

- A horizontal supply line H intersecting the h axis at point *hs* represents a conventional boiler plant which transfers *hs* (kWt) of heat

- A vertical supply line P, which intersects the ***p*** axis at point *ps* represents a conventional condensing power plant which generates *ps* (kWe) of electricity

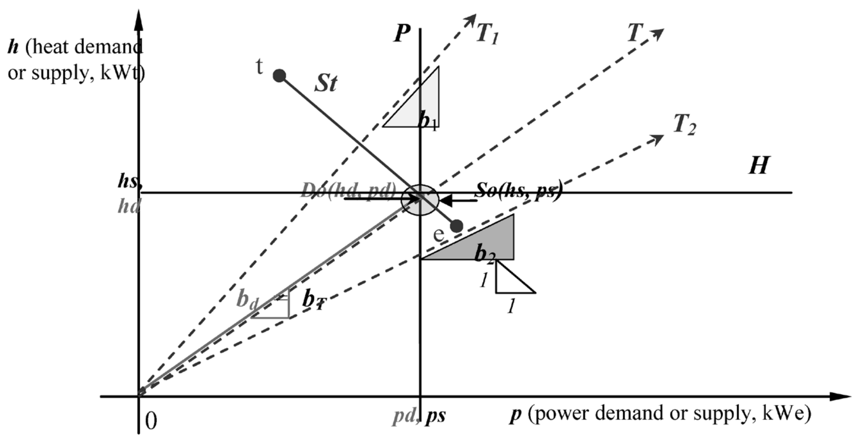

Figure 4. The CHP demand and supply space.

In Figure 4, the demand point is ***Do*** (hd, pd) defines a heat demand hd and a power demand pd. Hence, the total energy demanded by the host facility or process is D = hd+ pd (in kW). In order to supply heat and power to meet the demand ***Do*** we need a CHP technology ***T***, (Fig. 4, dotted lines----) which represents the commercially available machines with a heat-to-power ratio bS. Note that for a particular system of nominal size ***Si*** (kWe), applying first law of conservation of energy, we have

$$Ei = hs+ps+ls \quad (1)$$

Where:

Ei= Total primary energy rate input to System i. (kW)
ps= rated power available (kW)
hs= rated (maximum) heat available for process (kW)
ls= CHP system energy rate losses (kW).

TECHNOLOGY T AND SYSTEM S CURVES

In general, a specific CHP technology (say a diesel engine with heat recovery for process heating) is represented by a ***T*** line with a positive slope. Thus, a ***T*** line represents a family of commercially available CHP systems ***ST*** with a particular (nominal) heat-to-power ratio.

The line segment ***ST*** (bound by points **t** and **e**) represents a specific CHP system o machine, with a nominal psT (kWe) power capacity and maximum CHP output capacity *Eo which is the sum of the design (nominal maximum) heat* outputs *ps* and *hs*, respectively. The ***ST*** segment has a negative slope. Point t represents the maximum heat output capacity and point ***e*** the maximum power output capacity. Note the longer the ***ST*** line segment, the greater the supply heat-to-power flexibility; i.e. the line length indicates a range of heat to power S ratios. Thus, rearranging equation (1) as a function of ps, we have

$$h_s = Ei - (p_s + l_s) \quad (2)$$

Defining $\eta_e = ps/Ei$ as the power conversion efficiency we get

$$\eta_e = (Enom\text{-}hs)/(hs+ps+ls) \quad (3)$$

DESIGN AND EVALUATION CONSIDERATIONS

Next, we briefly discuss some of the relevant design and evaluation considerations, which will be studied and modeled to a greater extent in forthcoming articles. The considerations are:

- Technical Feasibility
- Economical Feasibility
- Reliability, Availability and Maintainability
- Economies of Scope and Integration
- Economies of Scale
- Systems with adjustable (supply) heat to power ratio

Technical Feasibility. Ideally, if a particular CHP technology ***T*** (Figure 4) meets exactly a site's heat and power needs (temperature and pressure, kW, etc.), then we say ***T*** is self-sufficient and technically feasible. Thus, the slope b_T (the supply or system heat-to-power ratio) matches exactly the slope bd (the demand heat-to-power ratio) defined by the demand segment **<u>0, *Do*</u>**. So,

$$b_d = b_T, p_s \geq p_d \text{ and } h_s \geq hd.$$

But a CHP system can be also be technically feasible, and economically attractive if it only meets a portion of the power or heat demands. This means the balance of the CHP load would have to be supplied by internal auxiliary (separate) heat or power generation units or by the electrical utility grid. *A robust methodology to know how much of the CHP demand should be served by the on-site cogeneration system and how much by internal auxiliary units or the utility is our underlying research mission*. Thus, given we have a set of suitable technologies ***T***, we need to know what is "the best" system size for a given site and how ought to be operated. Furthermore, we also want to find out if such system should export electricity, and how much, if any.

Notice in Figure 4 that if a particular CHP machine ***So*** is found (***So*** $\in$ ***T***) whose output coincides with the demand point ***Do***, then $h_s = h_d$ a and $p_s = p_d$. In this case, there is no need for heat and power imports and there are no heat and power surplus available for export. On the other hand, lines $\boldsymbol{T}_1$ and $\boldsymbol{T}_2$ (Figure 4) are examples of CHP technologies with slopes b_1 and b_2 which don't match the demand heat to power ratio or slope bd. In the case of $\boldsymbol{T}_1$ and $\boldsymbol{T}_2$, CHP imports may be required and exports may be possible.

Reliability, Availability and Maintainability (RAM). Since system ***To*** matches exactly the demand ***Do***, the system ***So*** and the served facility/process can conceivably operate isolated from the utility and without auxiliary boilers. However, a real system will likely require some back-up by having either additional on-site power generating units or utility back-up, during planned and unplanned maintenance down-times. Also, some heat back-up, in the form of auxiliary boilers may be needed. In the most general case, multiple reserve CHP units provide system redundancy. These RAM issues are addressed in a following article by using several degrees of system reserve capacity and/or multiple cogeneration units and the corresponding economic/engineering model.

Economies of Scale. So far we have assumed that a particular CHP technology or system is modeled by a straight line. However, over a wide range of system sizes, as the prime mover size increases, most CHP systems have a better fuel-to-power efficiency. This also means a lower heat-to-power ratio for the larger machines. Thus, for the CHP model **S**, the slope b_s decreases with system size. Such an "economy of scale" is better modeled by power **S** curves instead of straight **S** lines. Another economy of scale is the fact that, larger systems have lower per-unit installed costs ($/kW). Both of these issues will be dealt with in a forthcoming paper.

Systems with Flexible Heat-to-Power Output to Supply Variable CHP Demands. The (previous) apparently ideal case and model when $b_d = b_s$ can be achieved for a limited range of supply and demand heat-to-power ratios, by using flexible CHP technologies such those shown in Figure 6. In Figure 6, ***S1*** is a bottoming cycle industrial boiler with extraction and back-pressure steam turbine and ***S2*** is a gas-turbine topping cycle and an HRSG with limited but adjustable supplementary firing.

Flexible-output systems can provide a wide range of heat-to-power ratios, within technical and physical limits, and are represented by a family of CHP slopes. Such variable output systems are suitable when the on-site demand ***D*** is not constant and varies over time. For example, Figure 5 shows the hourly steam and electrical loads in a brewery. For variable loads, the CHP demand point *Do* roams within a region ***D,*** shown as an ellipse in Figure 6. In this case, a joint heat-and-power probability density function f(h,d) can be used to represent a bivariate random CHP demand within ***D***. In the future, we will use such probabilistic modeling to develop variable load and capacity models. Note in Figure 6 the ***S2*** system envelope can supply

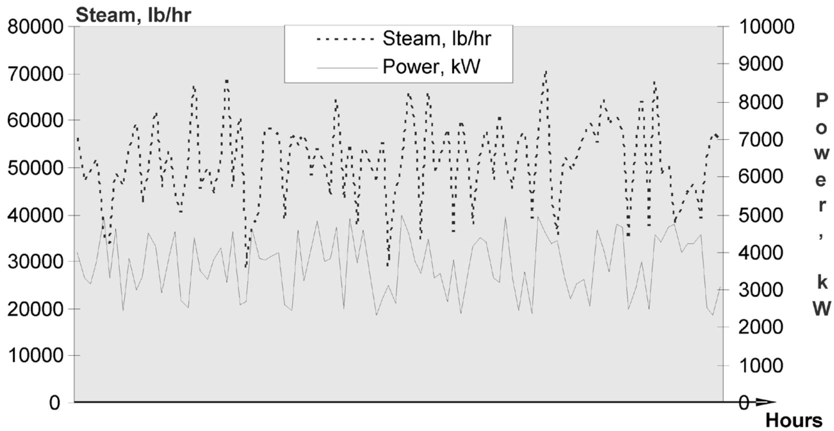

Figure 5. Hourly CHP Loads in a Brewery

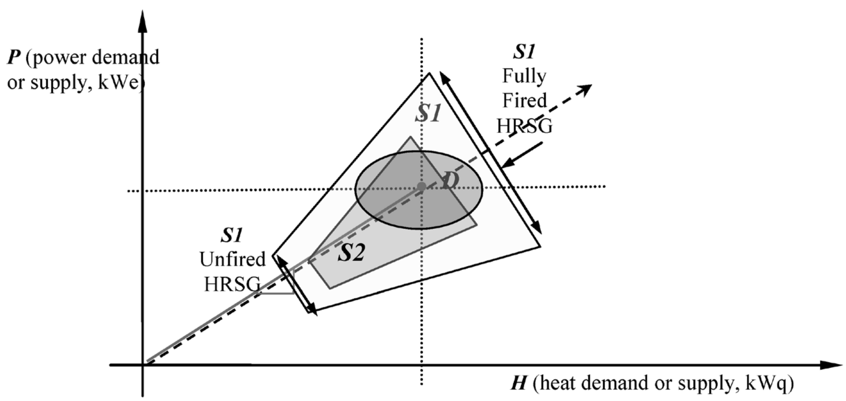

Figure 6. Two alternative CHP system technologies *S1* and *S2* can supply all or part of the variable CHP load or demand *D*

only part of the demand region ***D***; the balance of the load (not covered by ***S2***) has to be curtailed or supplied by the utility (power) or auxiliary units (heat).

Conversely, a larger and more flexible system like ***S1*** can supply the whole region ***D*** and is capable of exporting excess power or heat. However, such larger system (***S1***) will have higher installed and O&M costs than the smaller envelope system ***S2***. Note other systems ***Si*** can be technically feasible and define as a whole the feasible solution space *S*. *Note the models given herein help one find out which system S* (S* ε S) is the most cost effective.*

CONCLUDING REMARKS

This article has defined and depicted the CHP demand and supply model in the Cartesian space. Then Technology curves and System curves/ regions were introduced. Next, some relevant design and evaluation issues were discussed to set up the stage for model formulation. In the next article, Part 2, an economic optimization criterion will be developed. Note hte CHP space model is a basis for linear optimization of the CHP system size Pc (kWe). Future articles will show applications and extensions of the design optimization model proposed here.

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