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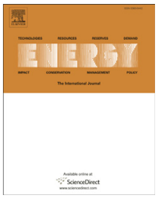

A simple sizing method for combined heat and power units

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ABSTRACT

We report a LDC (load duration curve) method to determine the optimum size of CHP (combined heat and power) units. The method gives the appropriate capacity graphically from the LDC of a building's heating demand. The method can be applied to the most common CHP units that are connected to the electrical grid, installed with thermal storage and auxiliary heat sources, and operated by a traditional heat-led strategy. The LDC method is simple and requires less information than existing sizing methods. Our method is in agreement with existing methods within 2.7–12.6% for internal combustion engine-driven CHP units, and 17.1–32.1% for Stirling engine-driven CHP units.

1. Introduction

When determining the size of generating, heating, ventilating, or air conditioning equipment, the first priority is to prevent supply failure. Economics is generally a secondary consideration. However, CHP (combined heat and power) units are virtually immune to supply failure, as they are commonly linked to the electrical grid and an auxiliary boiler. Thus, economic considerations become the first priority in determining the size of the unit. This problem is complicated, because both the distribution of the energy demand and the structure of energy pricing must be considered. The ratio of heat to electricity produced by a CHP unit differs from the ratio of heat to electricity consumed by the building; thus, under- or over-production of heat and/or electricity is inevitable. The sizing problem requires a profit/loss calculation due to the under- or over-production. This calculation involves nonlinear equations and increases the complexity of the problem.

We can divide previous reports on this topic into two groups according to their approach to the sizing (optimization) problem. The first group [1–9] has carried out simulations using energy analysis tools to estimate the operating parameters of the CHP units and to calculate the value of the objective function (for energy usage or for economics). This process is repeated for several facilities; the optimum capacity is obtained by comparing values of the objective function. The second group [10–21] has introduced an optimum design concept to reduce the computational expense or to obtain a global solution (with an extended range/number of design variables). To solve the sizing problem, both deterministic methods, including LP (linear programming) [10,11], MILP (mixed-integer linear programming) [12–16], and MINLP (mixed-integer nonlinear programming) [17,18], have been used, and stochastic search methods consisting of GA (genetic algorithm) [19] and PSO (particle swarm optimization) [20,21] methods. Thanks to improvements in energy analysis tools and optimum design techniques, the sizing problem can now be solved more accurately and efficiently. Nevertheless, existing methods are complex because they often require either comprehensive numerical analysis or additional modeling of the system and formulation of an optimum design. Moreover, these methods require detailed information such as high time-resolution load profiles, which introduces additional cost. Therefore, a simple sizing method that is easy to implement is desirable.

The purpose of this study is to develop a simple sizing method for CHP units. First, we classify the most common CHP systems and limit the scope of our sizing method. We also introduce assumptions that can be applied to the most common CHP systems. The scope limitation and assumptions result in a simpler objective function that is differentiable with respect to the size of the CHP unit. We can, therefore, obtain an optimum capacity by differentiating the objective function.

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Nomenclature

$\mathrm{AFC}_{\mathrm{CHP}}$	annual fixed cost of CHP system (USD)
$\mathrm{AFC}_{\mathrm{ref}}$	annual fixed cost of reference system (USD)
$\mathrm{AOC}_{\mathrm{CHP}}$	annual operating cost of CHP system (USD)
$\mathrm{AOC}_{\mathrm{ref}}$	annual operating cost of reference system (USD)
CDF	cumulative probability density function
c_{f}	fuel price (USD/kWh)
$c_{\mathrm{fix,CHP}}$	fixed cost per unit time and unit capacity (USD/kWh)
$c_{\mathrm{p,ex}}$	electricity selling price (USD/kWh)
$c_{\mathrm{p,im}}$	electricity purchase price (USD/kWh)
c_{q}	heating price (USD/kWh)
$F_{\mathrm{CHP,d}}$	fuel consumption of building during *d*th day (kWh)
i_{LDC}	index for the LDC method
$\mathrm{NAC}_{\mathrm{CHP}}$	net annual cost of CHP system (USD)
$\mathrm{NAC}_{\mathrm{ref}}$	net annual cost of reference system (USD)
$P_{\mathrm{CHP,d}}$	electricity production of CHP unit during *d*th day (kWh)
PDF	probability density function
$P_{\mathrm{load,d}}$	electricity consumption of building during *d*th day (kWh)
$Q_{CHP,\mathrm{d}}$	heat production of CHP unit during *d*th day (kWh)
$q_{\mathrm{CHP,nom}}$	CHP unit capacity in thermal rating (kW)
$q_{\mathrm{CHP,nom,opt}}$	appropriate capacity in thermal rating (kW)
$Q_{\mathrm{load,d}}$	heat production of CHP unit during *d*th day (kWh)
$q_{\mathrm{load,d}}$	daily average heat load of building (kW)
$r_{\mathrm{q,CHP}}$	revenue per unit heat production of CHP unit (USD/kWh)
$t_{\mathrm{CHP,d}}$	operating time of CHP unit for *d*th day (h)
t_{d}	length of *d*th day (24 h)
$\eta_{\mathrm{p,CHP}}$	electrical efficiency of CHP unit
$\eta_{\mathrm{q,CHP}}$	thermal efficiency of CHP unit
$\eta_{\mathrm{q,HOB}}$	thermal efficiency of heat only boiler
$\Delta\mathrm{AFC}_{\mathrm{CHP}}$	difference between annual fixed costs of CHP system and reference system (USD)
$\Delta\mathrm{NAC}_{\mathrm{CHP}}$	difference between net annual costs of CHP system and reference system (USD)

2. Methodology

We limited the scope of use and introduce additional assumptions to obtain a differentiable objective function. These limitations will be described in Section 2.1, where the system configuration is detailed. If we obtain a differentiable objective function without any constraints, the optimum solution can be obtained easily. Let the objective function be *f*, the CHP unit capacity be $q_{\mathrm{CHP,nom}}$, and the remaining variables be x_1, x_2, …. The optimum solution for $q_{\mathrm{CHP,nom}}$ is $q_{\mathrm{CHP,nom,opt}}$. If a function $f(q_{\mathrm{CHP,nom}}, x_1, x_2, \ldots)$ is differentiable in $q_{\mathrm{CHP,nom}}$, the solution $q_{\mathrm{CHP,nom,opt}}$ satisfies the following condition:

$$\frac{d}{dq_{\mathrm{CHP,nom}}} f\left(q_{\mathrm{CHP,nom,opt}}, x_1, x_2, \ldots\right) = 0 \tag{1}$$

An optimum design defines this condition as the first-order necessary condition for the unconstrained problem [22]. This condition is necessary because the function *f* can be either a local minimum or local maximum at $q_{\mathrm{CHP,nom,opt}}$. To determine whether the point is a minimum or maximum, we must check the conditions for an unconstrained problem. A typical optimum design formulates the objective function as the minimum [22]. We follow this convention, and the condition to minimize the objective function is as follows:

$$\frac{d^2}{dq^2_{\mathrm{CHP,nom}}} f\left(q_{\mathrm{CHP,nom,opt}}, x_1, x_2, \ldots\right) > 0 \tag{2}$$

If $q_{\mathrm{CHP,nom,opt}}$ satisfies this condition, then it is indeed an optimum [22]. If the condition is not satisfied, we must revise the higher-order conditions. For this reason, Eq. (1) is called the ‘first-order’ condition.

2.1. System configuration

The scope of the sizing method that we describe is limited to the most common CHP systems. We consider the most common CHP systems as follows.

Classification 1: (System composition) The CHP system is connected to the electricity grid, and is composed of a CHP unit (set of prime mover, generator, and heat recovery devices), a thermal storage unit, and an auxiliary heat source.

Classification 2: (Operating strategy) The CHP unit operates when heat demand exists, and the desired output is always the nominal output.

Classification 3: (Energy prices) All energy prices are fixed, and electricity from the CHP unit is sold according to a PPA (power purchase agreement), FIT (feed-in tariff), or net metering policy.

Here we give a more detailed explanation of these classifications.

Classification 1: HPR (ratio of heat to electricity) produced by the CHP unit differs from the HPR consumed by the building. During a 24-h day (the shortest period of the demand cycle that is observed in most buildings), if we fit the heat production of the CHP unit to the heat consumption of the building, then there will be differences between the electricity production of the CHP unit and the electricity consumption of the building (and vice versa). However, it is not difficult to choose which one (heat or power) should be fitted (or which one can be permitted to be out of balance). Electricity is easier to transfer than heat, and the transfer efficiency of electricity is higher than that of heat. Almost all CHP units are connected to the electrical grid, and can exchange over/under-produced electricity with the grid. This means that almost all CHP units fit heat production to heat consumption. However, there remains a short period (a few minutes to a few hours) where there is an imbalance between heat production and heat consumption. Therefore, almost all CHP units are installed with thermal storage and auxiliary heat source capacity. Fig. 1 shows the CHP system described by this classification.

Classification 2: If heat produced from the CHP unit is not used (i.e., it is dumped), then the energy efficiency of the CHP unit is less than that of the grid (conventional power plant). The CHP unit should not operate if heat produced from it is dumped. Except for operating strategies that only concern the customer’s profit (which are rarely applied), almost all operating strategies are designed not to dump heat. Traditional heating-led, the most widely applied operating strategy [23,24], avoids heat dumping by allowing the CHP unit to operate only when heat demand exists. Scheduled operation, which forecasts heat demand accurately and allows the CHP unit to operate to meet this demand, is also included in this classification. The performance and economics of the CHP unit are both maximized at the nominal output. The CHP units described by classification 1 are free to