

Efficiency Metrics for CHP Systems: Total System and Effective Electric Efficiencies

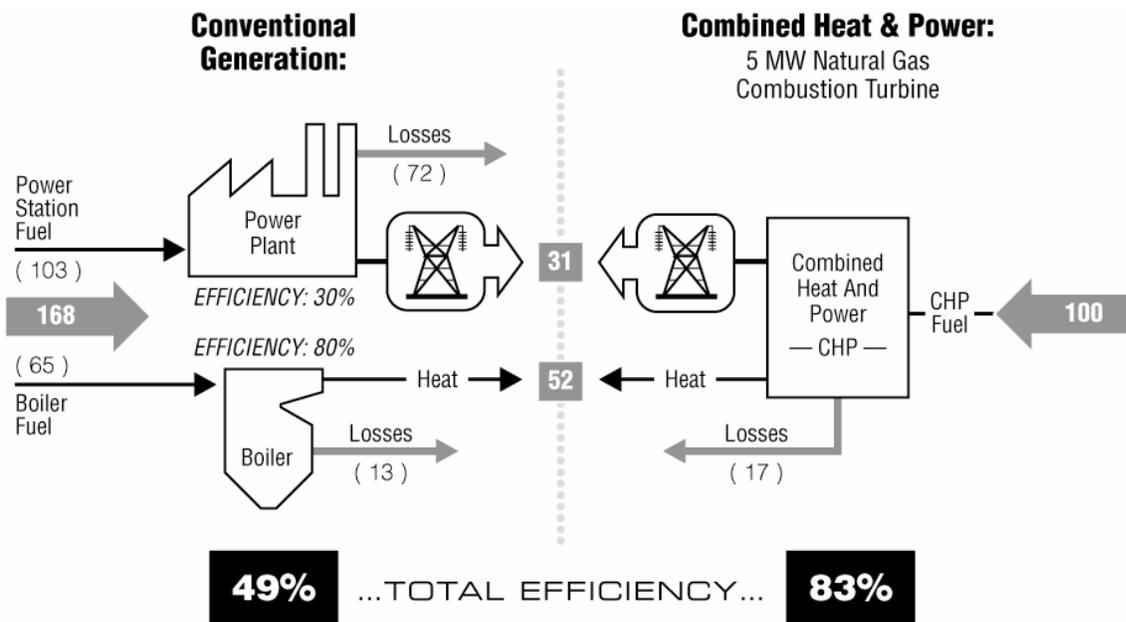
Combined heat and power (CHP) is an efficient and clean approach to generating power and thermal energy from a single fuel source. CHP is used either to replace or supplement conventional separate heat and power (SHP) (i.e., central station electricity available via the grid and an onsite boiler or heater).

CHP System Efficiency Defined

Every CHP application involves the recovery of otherwise wasted thermal energy to produce additional power or useful thermal energy. Because CHP is highly efficient, it reduces traditional air pollutants and carbon dioxide, the leading greenhouse gas associated with global climate change.

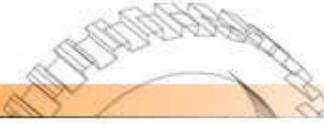
Efficiency is a prominent metric used to evaluate CHP performance and compare it to SHP. This white paper identifies and describes the two methodologies most commonly used to determine the efficiency of a CHP system: *total system efficiency* and *effective electric efficiency*.

The figure below illustrates the potential efficiency gains of CHP when compared to SHP.



Key Terms Used in Calculating CHP Efficiency

Calculating a CHP system’s efficiency requires an understanding of several key terms, described below.



- **CHP system.** The CHP system includes the unit in which fuel is consumed (e.g. turbine, boiler, engine), the electric generator, and the heat recovery unit that transforms otherwise wasted heat to useable thermal energy.
- **Total fuel energy input (Q_{FUEL}).** The thermal energy associated with the total fuel input. Total fuel input is the sum of all the fuel used by the CHP system. The total fuel energy input is often determined by multiplying the quantity of fuel consumed by the heating value of the fuel.

Commonly accepted heating values for natural gas, coal, and diesel fuel are:

- 1020 Btu per cubic foot of natural gas
 - 10,157 Btu per pound of coal
 - 138,000 Btu per gallon of diesel fuel
- **Net useful power output (W_E).** Net useful power output is the gross power produced by the electric generator minus any parasitic electric losses—in other words, the electrical power used to support the CHP system. (An example of a parasitic electric loss is the electricity that may be used to compress the natural gas before the gas can be fired in a turbine.)
 - **Net useful thermal output (ΣQ_{TH}).** Net useful thermal output is equal to the gross useful thermal output of the CHP system minus the thermal input. An example of thermal input is the energy of the condensate return and makeup water fed to a heat recovery steam generator (HRSG). Net useful thermal output represents the otherwise wasted thermal energy that was recovered by the CHP system.

Gross useful thermal output is the thermal output of a CHP system utilized by the host facility. The term *utilized* is important here. Any thermal output that is not used should not be considered. Consider, for example, a CHP system that produces 10,000 pounds of steam per hour, with 90 percent of the steam used for space heating and the remaining 10 percent exhausted in a cooling tower. The energy content of 9,000 pounds of steam per hour is the gross useful thermal output.

Calculating Total System Efficiency

The most commonly used approach to determining a CHP system's efficiency is to calculate *total system efficiency*. Also known as *thermal efficiency*, the total system efficiency (η_o) of a CHP system is the sum of the net useful power output (W_E) and net useful thermal outputs (ΣQ_{TH}) divided by the total fuel input (Q_{FUEL}), as shown below:

$$\eta_o = \frac{W_E + \sum Q_{TH}}{Q_{FUEL}}$$

The calculation of total system efficiency is a simple and useful method that evaluates what is produced (i.e., power and thermal output) compared to what is consumed (i.e., fuel). CHP systems with a relatively high net useful thermal output typically correspond to total system efficiencies in the range of 60 to 85 percent.

Note that this metric does not differentiate between the value of the power output and the thermal output; instead, it treats power output and thermal output as additive properties with the same relative value. In reality and in practice, thermal output and power output are not interchangeable because they cannot be converted easily from one to another. However, typical CHP applications have coincident power and thermal demands that must be met. It is reasonable, therefore, to consider the values of power and thermal output from a CHP system to be equal in many situations.

Calculating Effective Electric Efficiency

Effective electric efficiency calculations allow for a direct comparison of CHP to conventional power generation system performance (e.g., electricity produced from central stations, which is how the majority of electricity is produced in the United States). Effective electric efficiency (ϵ_{EE}) can be calculated using the equation below, where (W_E) is the net useful power output, ($\sum Q_{TH}$) is the sum of the net useful thermal outputs, (Q_{FUEL}) is the total fuel input, and α equals the efficiency of the conventional technology that otherwise would be used to produce the useful thermal energy output if the CHP system did not exist:

$$\epsilon_{EE} = \frac{W_E}{Q_{FUEL} - \sum (Q_{TH} / \alpha)}$$

For example, if a CHP system is natural gas fired and produces steam, then α represents the efficiency of a conventional natural gas-fired boiler. Typical α values for boilers are: 0.8 for natural gas-fired boiler, 0.75 for a biomass-fired boiler, and 0.83 for a coal-fired boiler.

The calculation of effective electric efficiency is essentially the CHP net electric output divided by the additional fuel the CHP system consumes over and above what would have been used by conventional systems to produce the thermal output for the site. In other words, this metric measures how effectively the CHP system generates power once the thermal demand of a site has been met.

Typical effective electrical efficiencies for combustion turbine-based CHP systems are in the range of 51 to 69 percent. Typical effective electrical efficiencies for reciprocating engine-based CHP systems are in the range of 69 to 84 percent.



Which CHP Efficiency Metric Should You Select?

The selection of an efficiency metric depends on the purpose of calculating CHP efficiency.

- If the objective is to compare CHP system energy efficiency to the efficiency of a site's SHP options, then the **total system efficiency metric** may be the right choice. Calculation of SHP efficiency is a weighted average (based on a CHP system's net useful power output and net useful thermal output) of the efficiencies of the SHP production components. The separate power production component is typically 33 percent efficient grid power. The separate heat production component is typically a 75- to 85-percent efficient boiler.
- If CHP electrical efficiency is needed for a comparison of CHP to conventional electricity production (i.e., the grid), then the **effective electric efficiency metric** may be the right choice. Effective electric efficiency accounts for the multiple outputs of CHP and allows for a direct comparison of CHP and conventional electricity production by crediting that portion of the CHP system's fuel input allocated to thermal output.

Both the total system and effective electric efficiencies are valid metrics for evaluating CHP system efficiency. They both consider all the outputs of CHP systems and, when used properly, reflect the inherent advantages of CHP. However, since each metric measures a different performance characteristic, use of the two different metrics for a given CHP system produces different values.

For example, consider a gas turbine CHP system that produces steam for space heating with the following characteristics:

Fuel Input (MMBtu/hr)	41
Electric Output (MW)	3.0
Thermal Output (MMBtu/hr)	17.7

Using the total system efficiency metric, the CHP system efficiency is 68 percent $(3.0 \times 3.413 + 17.7) / 41$.

Using the effective electric efficiency metric, the CHP system efficiency is 54 percent $(3.0 \times 3.413) / (41 - (17.7 / 0.8))$.

This is not a unique example; a CHP system's total system efficiency and effective electric efficiency often differ by 5 to 15 percent.

NOTE: Many CHP systems are designed to meet a host site's unique power and thermal demand characteristics. As a result, a truly accurate measure of a CHP system's efficiency may require additional information and broader examination beyond what is described in this document.

For More Information

Additional information about CHP applications and technologies can be found on the EPA CHP Partnership Web site at: www.epa.gov/chp.