OR-10-039

Energy Systems Management and Greenhouse Gas Reduction

Stephen J. Treado, PhD, PE
Member ASHRAE

David Holmberg, PhD
Member ASHRAE

ABSTRACT

The efficient use of energy reduces both energy costs and greenhouse gas (GHG) emissions, and the mix of energy sources can also affect GHG emissions. In the United States, the building sector comprises about one third of GHG emissions [1], presenting an attractive opportunity for utilizing advanced design, operation and control strategies to minimize energy consumption and emissions while optimizing overall system performance through the implementation of cogeneration, heat recovery, adaptive controls and other advanced techniques. This paper presents an approach for controlling GHG emissions and energy consumption through improved communication between energy consumers and suppliers, and advanced energy management systems. A specific example involving cogeneration is detailed to demonstrate the concept.

INTRODUCTION

Modern society is built on energy technologies to provide a comfortable and safe environment, and to produce desirable goods and services. There are many different ways to identify, categorize and subdivide energy consuming sectors. Two examples are on the basis of end use, such as heating, cooling, lighting or manufacturing, or on the basis of the general class of activity, such as transportation, industrial or buildings. However, regardless of how the energy consumption is categorized, the efficient use of energy is desirable. Focusing on energy efficiency as a means to control energy usage, rather than a simple reduction in energy consumption, allows us to meet our broader economic goals without sacrificing performance desired from the activity.

The link between energy efficiency and GHG emissions is clear. The principal GHG of concern is CO_2, a product of carbon-based fuels combustion. Thus, both the efficiency of fuel burning devices and the efficiency of devices that use energy produced by other devices that burn fuel, affect GHG emissions. Taking a broader view, the efficiency of all the various processes in an energy conversion chain influences the total energy requirements, and therefore the associated GHG emissions.

ENERGY MANAGEMENT SYSTEMS

There are multiple factors which can influence energy efficiency and performance. The efficiencies of combustion and mechanical energy conversion equipment and systems can vary with load and other operating conditions, both at the supplier and consumer ends of the supply chain. As a result, maintaining efficient system operation usually requires an energy management system (EMS) which can measure and manipulate essential system parameters [2]. Modern EMS's may also be capable of communicating with utilities, weather forecasters, and other entities in order to perform sophisticated control actions, including load shedding, fuel switching, and other proactive measures. In order to make proper decisions and maintain optimum system operation, the EMS must be able to access the required information and have a means to evaluate various modes of operation and manipulate operating conditions. This capability implies a level of intelligence that is certainly feasible, but only recently seeing increased implementation.

EMS optimization goes beyond simple feedback control of individual processes, or even cascaded loop control, and ventures into intelligent hierarchical control strategies that can consider overall system performance, and adjust, activate or

Stephen Treado and **David Holmberg** are mechanical engineers with the National Institute of Standards and Technology, Gaithersburg, MD.

terminate processes as required [3]. Some of the EMS-based strategies to reduce energy usage and GHG emissions include:

- Controlling equipment and systems for higher efficiencies
- Reducing loads
- Shifting loads to off-peak time periods
- Energy storage
- Heat recovery
- Energy source selection

Methods such as cogeneration (combined heat and power), heat recovery and fuel switching can have a large impact on GHG emissions. Determining the optimum operating conditions requires careful consideration of many factors, including the carbon content of the fuel sources, emissions characteristics, and the efficiencies and controllability of the various systems and components.

The link between EMS and GHG reductions lies in the ability to monitor the critical source and site parameters that affect energy usage, energy efficiency and emissions. Some of these opportunities can be implemented in a straightforward manner without any special or advanced features or capabilities. For example, reducing energy consumption by reducing loads or increasing energy efficiency will reduce GHG emissions. Switching from higher to lower carbon content energy sources will also reduce GHG emissions. If various energy source alternatives are available onsite, their selection can be based on information that is readily available locally. If, however, the energy source alternatives include one or more offsite sources, in addition to the algorithms required to compare the source emissions, a communications capability that provides access to energy source carbon content or emissions characteristics would be required. The key point is that the EMS would not be simply monitoring and maintaining operating conditions such as temperatures and airflows, but would be continuously evaluating energy source alternatives to minimize emissions, or some combination of emissions, energy usage and energy costs.

UTILITY INTERACTIONS AND SMART GRID

A relatively recent, and ongoing, development involves real-time communication between the building EMS and utilities via the internet, private network or other secure channel, a concept know as smart grid. This type of technology would enable end users (consumers) to obtain current information from different utilities regarding parameters such as pricing and emissions, including CO_2, as shown in Figure 1. In this figure, each utility could have a different average rate of CO_2 production per unit of electrical power, $\bar{C}$ (kg/s-kW)(lb/s-kW), since the power could be coming from a different mix of sources including fuel-fired plants or renewable resources. These values could also vary with time of day, weather conditions and operational factors, so a continuous updating would be required to stay current. There may also be merit in providing a value for the marginal CO_2 emissions for the utility, since that would correspond to the emissions associated with providing an additional increment or decrement of electrical power, however the use of this factor would be complicated since overall utility power demand is constantly changing, and the marginal contribution of each power source, along with the combined marginal value, might be difficult to determine. Armed with the relevant emissions information along with other real time data such as costs, one way or another end users could elect to obtain their electrical power from the supplier they deem to be most appropriate, based on energy cost, emissions or other relevant parameter, or alternatively where available, generate their own electrical power.

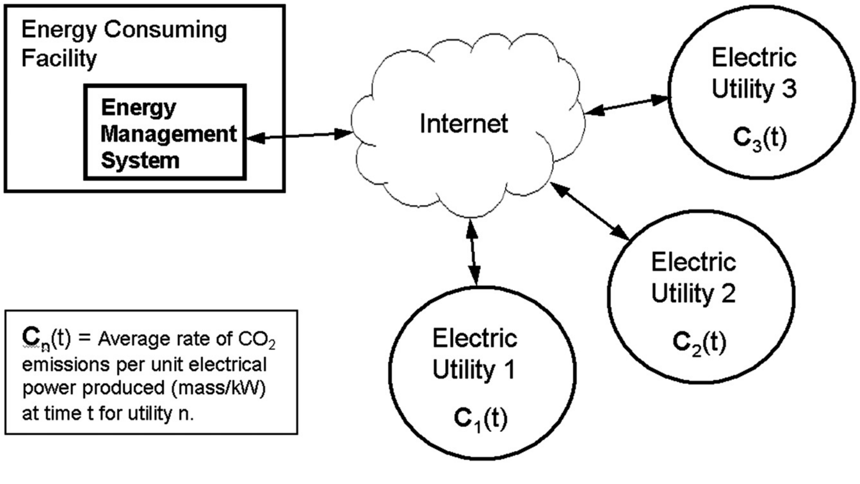

Figure 1 *Communicating emissions information between utilities and end users.*

ASHRAE BACnet is addressing the tools that enable the commercial building or facility to communicate with utilities. ASHRAE and many other organizations are together involved in a collaborative process to address communication standards under the NIST-lead smart grid effort. NIST was given the mandate by the 2007 EISA legislation to coordinate smart grid standards interoperability. NIST has outlined the information content into a knowledge base, and brought together expert working groups to address the process for achieving standards interoperability. Details of the process and status of this effort can be found on the NIST website at: http://www.nist.gov/smartgrid/. Some of the standards that are being addressed that are pertinent to consumers include pricing and quality. Quality has different aspects including source characteristics, voltage regulation (peaks, mean, frequency, phase), and prediction of near-term quality.

ENERGY USE AND GHG EMISSIONS

The total energy used by an enterprise may be composed of a number of components, but typically consists of a combination of electrical power and thermal energy resulting from on-site or external combustion of fossil fuels. In some cases, there may also be a source of electrical power from a renewable resource such as solar photovoltaic or wind power, or possibly a renewable heated fluid source, such as geothermal or solar thermal power. Another option is the on site generation of electrical power from a fuel source, such as a gas turbine or diesel engine, which may be accompanied by a byproduct source of heated fluid, a strategy called cogeneration. A schematic representation of offsite power generation with onsite heat source, compared to a cogeneration system, is given in Figure 2.

The GHG emissions that are associated with each of these energy sources can vary substantially, both compared to each other, and over time, as a function of the carbon content of the fuel. For example, electrical power generated by a coal-fired power plant would have a high CO_2 emission rate, while hydroelectric power would have essentially zero, while a natural gas fired generator would fall somewhere in between. The combined CO_2 emission rate is a function of the particular mix of generating technologies in operation at any given time.

When trying to evaluate the GHG emissions associated with the use of electrical power generated remotely, it is necessary to know the effective carbon content or emissions characteristics of the mix of power generation sources. This evaluation is largely an accounting exercise, since power is fed into utility and regional power grids from many sources, and extracted by multiple consumers. It should be possible for a utility to obtain an estimate of the percentage contributions of each type of power generation, and from that determine the rate of CO_2 production as a function of electrical power produced, as well as a value for the marginal emissions. However, these values can vary with time as different reserves are brought online to meet varying power demand [4]. Typical values for coal fired power plants are about 0.95 kg/kW-h (2.1 lb/kW-h), 0.90 kg/kW-h (2.0 lb/kW-h) for oil fired, and 0.6 kg/kW-h (1.3 lb/kW-h) for gas fired, while the U.S. average is only 0.61 kg/kW-h (1.3 lb/kW-h) due to the contribution from non-emitting sources (hydro, nuclear and renewable).

As mentioned above, average or marginal values could be used to represent emissions. Similar values can be obtained for each primary energy source (i.e. each fuel source) for on site combustion. By comparing the CO_2 emission rates of the various energy sources, along with the conversion efficiencies, the mix of energy sources that minimizes GHG emissions can be determined. As a side note, it would also be possible to optimize total energy usage, energy cost, or any combination of the three parameters.

As an example of a change in operation in response to real time utility data is shown in Table 1, referring to Figure 1. Utility emissions indicators are monitored and as they change over time, the most favorable source can be selected.

HEAT RECOVERY, ENERGY STORAGE AND RENEWABLE ENERGY SOURCES

One of the advantages of on site power generation is the potential for combined heat and power systems (cogeneration). The large-scale electrical power version of this concept is known as district heating [5]. In either case, a fuel is burned to generate heat which powers a generator, and subsequently the waste heat is utilized for water, space or process heating. The combined efficiency of such a system exceeds that of power generation alone. Depending on the circumstances, the use of cogeneration may result in lower GHG emissions, especially when the CO_2 emission rate of the electric utility is high, and there is a need for the waste heat from the power generation. This scenario will frequently be the case for industrial installations, since process heating requirements can be very large. This approach would not be favored, however, for industrial applications that have high electrical power requirements relative to heating requirements, since the heat rejected by the power conversion system would not be in demand.

Energy storage is another concept that can be particularly beneficial. Whenever heating loads are variable and do not necessarily coincide with the availability of thermal energy, heat storage can increase overall system efficiency by allowing thermal energy to be stored and recovered for later use, thereby moving it from the waste to the useful category. Energy usage can also be shifted to times when the carbon content of the energy source is lower.

Renewable energy sources are always beneficial from a GHG reduction perspective, since they are assumed to have no net contribution to CO_2 production, and the energy they produce will substitute for energy sources that do emit GHG's. While higher renewable energy conversion efficiencies are beneficial, the actual efficiency has only an indirect effect on emissions due to the substitution of carbon-free renewable energy for non-renewable fossil fuels. Since renewable sources such as wind and solar radiation are essentially free,

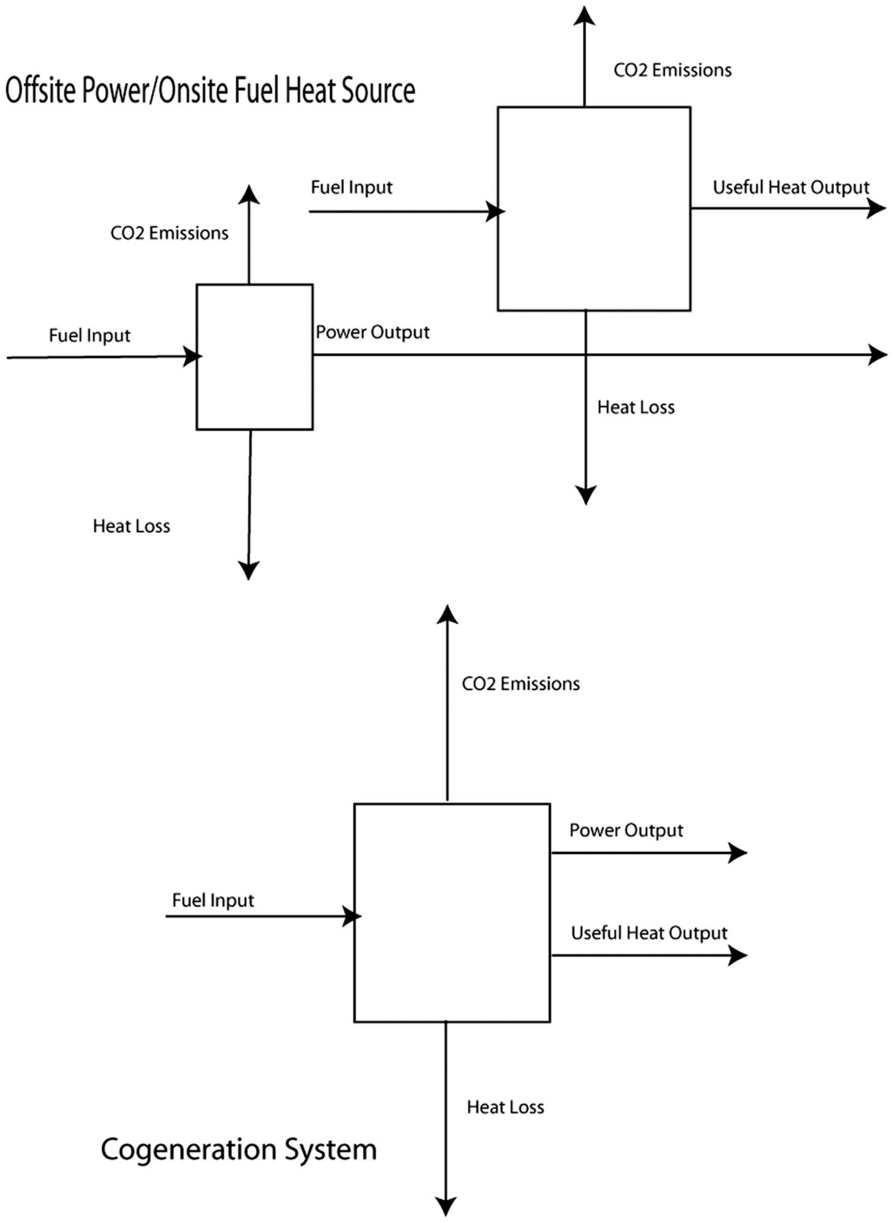

Figure 2 *Schematic diagram of alternative system configurations for providing electrical power and heating energy.*

Table 1. Building Operation Response to Real time Utility Emissions Data

Time	$\bar{C}_1$ (mass/s-kW)	$\bar{C}_2$ (mass/s-kW)	$\bar{C}_3$ (mass/s-kW)	Utility Selection
1	$2.64\ (10^{-4})$	$2.5\ (10^{-4})$	$1.67\ (10^{-4})$	Utility 3
2	$2.64\ (10^{-4})$	$2.0(10^{-4})$	$1.8(10^{-4})$	Utility 3
3	$2.64\ (10^{-4})$	$1.9\ (10^{-4})$	$2.0\ (10^{-4})$	Utility 2
4	$1.6\ (10^{-4})$	$1.8\ (10^{-4})$	$2.2\ (10^{-4})$	Utility 1

the conversion efficiency of renewable technologies is not as critical as the energy conversion efficiency of costly fuels.

Example—Cogeneration and GHG Emissions

One illustrative example of the potential for an EMS to reduce GHG emissions involves selecting between offsite (electric utility) electrical power combined with onsite fuel based heating, and onsite cogeneration (combined heat and power), on the basis of the CO_2 emissions. The values used in this example were selected to demonstrate the method rather than to specifically evaluate the competing technologies, but are within the range typically encountered. The metric for analysis is the rate of CO_2 production for an equivalent output of power and useful heat. The rate of CO_2 production ($\dot{m}_{CO_2}$) is a function of the rate of the fuel used ($\dot{m}_F$) the carbon content (C, m_C/m_F), and the combustion (η_{comb}) and system (η_o) efficiencies. Based on stochiometric considerations, every kilogram of carbon consumed produces 3.67 kg of CO_2, since the ratio of the molecular weights of CO_2 and carbon is 44/12. Thus:

$$\dot{m}_{CO_2} = 3.67C\dot{m}_F \tag{1}$$

Since the electrical power (P_{EL}) delivered to the site is equal to the rate of energy release from the fuel consumed times the system efficiency (η_o), which includes thermal, generation and transmission efficiencies, the rate of CO_2 production associated with a delivered electrical power of P_{EL} is given by:

$$\dot{m}_{CO_2} = 3.67C \cdot P_{EL}/(\eta_o HV) \tag{2}$$

where HV- heating value of the fuel (either higher or lower HV as applicable), kJ/kg (Btu/lb), and C is related to the utility supplied value of $\bar{C}$ according to:

$$C = \frac{\bar{C} \cdot \eta_o \cdot HV}{3.67} \tag{3}$$

A similar relation holds for the rate of onsite CO_2 production from combustion of fuel to produce heat, with the exception that system efficiency is replaced by combustion efficiency. This difference is significant, since the system efficiency of grid-supplied electrical power is in the range of 25 to 40%, while combustion efficiencies are 70 to 90% [5].

The energy performance of cogeneration systems can be characterized by the Energy Utilization Factor (EUF) [6], which is the ratio of the sum of the electrical power and the rate of useful heat ($\dot{Q}_U$) produced to the rate of energy input from the fuel consumed ($\dot{Q}_F$) (i.e., $EUF=(P_{EL} + \dot{Q}_U)/\dot{Q}_F$), and the Heat to Power Ratio (HPR), which is simply $\dot{Q}_U/P_{EL}$. Combining these two parameters results in:

$$\dot{Q}_F(EUF) = P_{EL} + \dot{Q}_U = P_{EL} + (HPR)P_{EL} = P_{EL}(1 + HPR) \tag{4}$$

Using eqn. (1) and the fact that $\dot{Q}_F = \dot{m}_F$ (HV), the rate of CO_2 production by the onsite cogeneration system is given by:

$$\dot{m}_{CO_2, CG} = \frac{3.67C \cdot P_{EL}}{HV}\left(\frac{1 + HPR}{EUF}\right) \tag{5}$$

The total CO_2 production rate for the offsite electrical power plus the onsite fuel-based heating includes two terms, as follows:

For offsite power, use the following equation:

$$P_{EL} = \dot{m}_F \cdot HV \cdot \eta_o = \dot{m}_{CO_2} \cdot HV \cdot \eta_o/(3.67C)$$

$$\text{so, } \dot{m}_{CO_2} = 3.67C \cdot P_{EL}/(HV \cdot \eta_o) \tag{6}$$

For onsite heating, use the following equation:

$$\dot{Q}_U = \dot{m}_F \cdot HV \cdot \eta_{comb} = \dot{m}_{CO_2} \cdot HV \cdot \eta_{comb}/(3.67C)$$

$$\text{so, } \dot{m}_{CO_2} = 3.67C \cdot \dot{Q}_U/(HV \cdot \eta_{comb}) \tag{7}$$

Combining eqns. (6) and (7) yields:

$$\dot{m}_{CO_2, Off} = \frac{3.67C \cdot P_{EL}}{HV}\left(\frac{1}{\eta_o} + \frac{HPR}{\eta_{comb}}\right) \tag{8}$$

Equations 5 and 8 differ in the efficiency terms, and in the fact that in equation 5, HPR and EUF are linked (see below). The two equations can be used to compare CO_2 generation for the two alternatives. A simple comparison metric is the ratio of $\dot{m}_{CO_2, Off}/\dot{m}_{CO_2, CG}$.

In order to first focus on the system effects, as opposed to the fuel or component effects, in the following example fuel type is held constant. Other assumptions include efficiency values and electrical power and heat requirements (these values are not necessarily typical, but are given only for the purpose of demonstrating the procedure):

- All fuel sources were natural gas, with HV=50MJ/kg (21,500 Btu/lb), C=0.75, η_{comb}=0.80
- Electrical power requirement was constant at 1MW, but the heat requirement was varied
- The system efficiency for the offsite power generation was varied in three steps, 0.26, 0.35 and 0.40 (this has the same effect on emissions as varying the carbon content of the fuel)
- The electrical generation efficiency for the cogeneration system was held constant at 0.26
- The baseline conditions for the cogeneration system were EUF=0.85 for HPR=2.2. HPR was varied in increments of 0.2 to simulate decreased heating requirements
- As the amount of heat needed onsite decreased, EUF was adjusted to maintain a constant ratio of $EUF/(1+HPR) = P_{EL}/Q_F = 0.26$. This represents heat that is available from the onsite power generation, but not utilized because it is not needed.

Figure 3 shows the results for an offsite power system efficiency of 0.26 compared to the cogeneration case, over a range of heating requirements, as represented by the *HPR*. The plots include CO_2 production rates for the two alternatives, and the emission ratio, the ratio of offsite to cogeneration CO_2 production (CO_2 production for the offsite system includes both power plant and onsite emissions from the local fuel-based heating system). For these conditions, the cogeneration system produces less CO_2 over the full range, and is better by a factor of greater than 1.7 for the highest *HPR* that was considered. This result occurs because the cogeneration system is sized to always be able to meet any heating load associated with a *HPR* less than 2.2, so all of the cogenerated heat is utilized. By comparison, the offsite power system relies on the local heating system to provide the required heat, so its CO_2 production increases with heating load.

Figure 4 shows similar results for three offsite power system efficiencies. It is clear that as system efficiency increases, or the carbon content of the offsite fuel decreases, the offsite power generation produces less CO_2 at lower values of HPR than the cogeneration system (i.e. CO_2 ratio is less than one). This outcome occurs because the cogeneration system has to maintain full output to meet the electrical power load, thereby generating excess heat, while the offsite/onsite heating system can reduce output to match the heating load. These results are just examples, since actual values would depend on the systems and conditions being compared, particularly the carbon content and relative efficiencies of the combustion processes.

Table 1 presents the effect that different offsite and onsite fuel sources would have on relative emissions for natural gas, coal and oil, based on typical values for C and HV for each fuel source, and assuming equal combustion efficiencies. From the ratio of equations (8) to (5), it can be shown that the change in relative emissions would be equal to the ratios of C/HV for the offsite and onsite fuel sources. The values for C/HV are 0.049 $(\text{kW-h})^{-1}$ for natural gas, 0.075 $(\text{kW-h})^{-1}$ for coal and 0.064 $(\text{kW-h})^{-1}$ for oil. The previous results presented for the case when both the offsite and onsite fuel sources are natural gas can be converted to other fuel source combinations by multiplying by the appropriate factors given in Table 2. For example, if the offsite fuel source were natural gas and the onsite fuel source coal, the emissions ratios in Figures 3 and 4 would be adjusted by a factor of 0.65, making the offsite generation much more favorable.

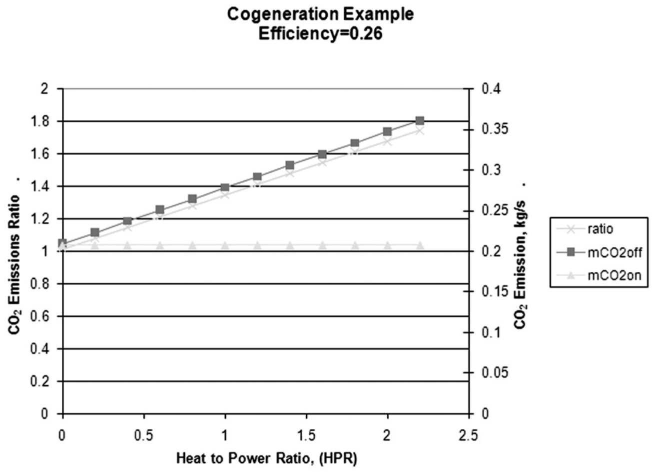

Figure 3 *CO_2 emissions and emission ratio for offsite power generation with onsite heating versus onsite cogeneration.*

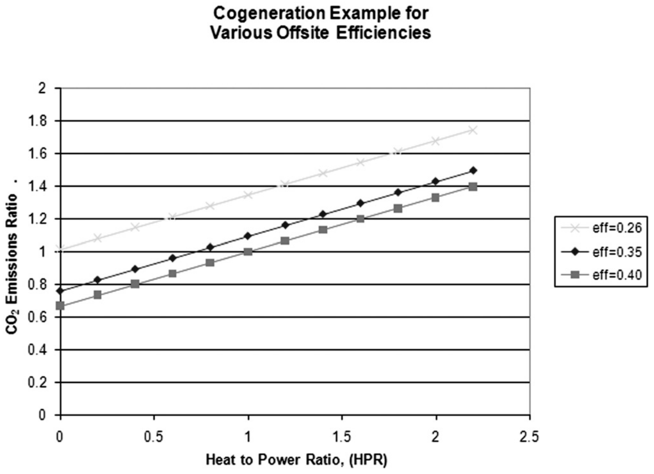

Figure 4 *CO_2 emission ratios for offsite power generation with onsite heating versus onsite cogeneration for various offsite power generation efficiencies.*

Table 2. Multiplication Factors for Different Fuel Source Combinations

Onsite Fuel Source	Natural Gas	Coal	Oil
Offsite Fuel Source			
Natural Gas	1	0.65	0.77
Coal	1.53	1	1.17
Oil	1.31	0.85	1

While not part of this analysis, the addition of a heat storage capacity could improve the cogeneration performance, provided that there was a recurring need for thermal energy that could be provided by excess heat recovered from storage. There are many other ways that energy and emissions performance could be improved based on specific circumstances and operating characteristics, and these functions can be implemented via the EMS.

While the above analysis used single values for system efficiency, in a real world case, it would be better to use an average value that was representative of the mix of electrical power sources feeding the grid at any point in time. Developments currently underway, such as Smart Grid [7], could enable the EMS could monitor this and other information using Internet resources, allowing decisions based on current conditions, determining when it made sense to use the onsite capacity, and when it made sense to use the offsite capacity. These decisions could be based on any combination of energy, environmental and cost factors.

CONCLUSIONS

Energy management systems have great potential for reducing GHG emissions as well as energy usage by monitoring and manipulating the operation of energy consuming systems. There are many approaches that are available for taking advantage of the carbon characteristics of the energy sources to minimize the GHG emissions associated with a particular onsite energy usage profile. For example, utilizing cogeneration, heat recovery, fuel switching and energy storage can be effective measures provided that the sensing and control capabilities are incorporated into the EMS, and suitable algorithms are available for comparing alternatives under dynamic conditions. Information is increasingly becoming available via the Internet to enable the determination of the most effective operating strategies as both source and site characteristics change with time.

This paper demonstrated a method for evaluating the GHG impact of different sources of facility electrical power and process heat. The results showed that trade-offs of GHG emissions can be performed if utility emissions information is available and can be obtained in real time through the internet or private network. The results also suggest that in some cases, cogeneration can result in a significant reduction in GHG emissions, although the relative performance is strongly dependent on the energy conversion efficiencies and the carbon content of the energy sources.

REFERENCES

IPCC, 2007: Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK, and New York, USA.

Capehart, B.L., Turner, W.C., Kennedy, W.J., Guide to Energy Management, 5th Edition, The Fairmont Press, 2006.

Haines, R.W., Hittle, D.C., Control Systems for Heating, Ventilating and Air Conditioning, 6th Edition, Kluwer Academic Publishers, 2003.

U.S. Department of Energy, Carbon Dioxide Emissions from the Generation of Electric Power in the United States, July 2000

Sorensen, B., Renewable Energy, Third Edition, Elsevier Academic Press, Burlington, MA, 2004.

Khartchenko, N. V., Advanced Energy Systems, Taylor and Francis, Washington, DC, 1998.

NEMA, http://www.nema.org/gov/energy/smartgrid/whatIsSmartGrid.cfm