OPTIMIZATION FOR COGENERATION SYSTEMS IN BUILDINGS BASED ON LIFE CYCLE ASSESSMENT

SUBMITTED: March 2005
REVISED: January 2006
PUBLISHED: May 2006 at http://itcon.org/2006/20/
EDITOR: Dana J. Vanier

Ayat E. Osman, PhD. Candidate
University of Pittsburgh, Department of Civil and Environmental Engineering
email: aeo2@pitt.edu

Robert Ries, Assistant Professor
University of Pittsburgh, Department of Civil and Environmental Engineering
email: robries@pitt.edu

SUMMARY: *This paper presents a model that is developed to optimize the selection and operation of energy systems in commercial buildings based on their environmental performance. The model can be used for decision support regarding infrastructure in both design and operation of building energy systems. The approach is composed of energy simulation to generate building's energy demand, life cycle assessment (LCA) to model different energy systems, and optimization model to optimize the selection and operation of these energy systems. The energy systems that are discussed in this paper are cogeneration systems, average electric grid, gas boilers, and absorption and electric chillers. The performance criteria presented in this paper are primary energy consumption (PEC) and tropospheric ozone precursor potential (TOPP).*

KEYWORDS: *cogeneration, life cycle assessment, optimization.*

1. INTRODUCTION

Commercial buildings in the US are one of the largest sectors that purchase electricity. On average, the commercial and residential sectors pay significantly more for electricity than the industrial sector, mainly because some of the industrial sectors generate their own electricity (A. D. Little, 2000). The significant environmental impacts resulting from the operation of buildings have been reported by the U.S. Department of Energy: building operations represent approximately 40% of the annual total energy consumption in the United States with approximately equal proportion of the annual related carbon dioxide production (37%) (U.S. DOE, 2003). Approximately 2236.2 million Metric tones (MMT) of carbon dioxide emissions from residential (1,212.0 MMT) and commercial (1,024.2 MMT) is due to U.S. energy-related carbon dioxide emissions in 2004 (EIA, 2004). Carbon dioxide is one of the most important greenhouse gases (GHG): -- gases that trap the solar heat close to the Earth's surface and absorb infrared radiation at particular wavelength. The Intergovernmental Panel on Climate Change (IPCC) developed the global warming potential (GWP) concept to measure the impacts of different GHG on global warming by normalizing these gases relative to carbon dioxide based on their radiative forcing, which is given the equivalence of 1 unit (IPPC, 2001). Other GHG that contribute to GWP are: (a) nitrogen oxides, totalling 1130 thousand metric tons (TMT) carbon dioxide equivalent (815 TMT originate from residential energy related activities and 315 TMT carbon dioxide equivalent from commercial sources); and (b) methane, totalling 7087 TMT carbon dioxide equivalent (6,968 TMT carbon dioxide equivalent from residential sources and 119 TMT carbon dioxide equivalent from commercial sources) (EIA, 2004). Therefore by summing these numbers, the total GWP resulting from residential and commercial energy related activities considering carbon dioxide, nitrogen oxides and methane emissions is 2244 MMT carbon dioxide equivalent.

In commercial buildings, natural gas is recognized as the principal fuel for space and water heating, with electricity generated off-site used for cooling loads, lighting needs, office and other equipment. Using natural gas-fired cogeneration systems will allow commercial buildings not only to generate their own electricity but also to use energy efficiently because these technologies can utilize the otherwise wasted thermal energy for a variety of purposes, such as space and water heating as well as cooling with absorption chillers. In addition to energy efficiency that results in lower primary energy resource consumption, natural gas-fired cogeneration systems emit fewer pollutants than conventional coal- and oil-fired systems. This is because natural gas has a lower sulfur, nitrogen, and carbon content than coal resulting in lower emissions.

Management of cogeneration systems is usually performed to minimize costs. Minimal consideration is given to optimizing the management of these systems with regards to environmental criteria. A study on energy management strategies for existing cogeneration systems showed that these systems were not profitable due to a lack of a strong energy management strategy and the systems operation was constrained by the very complex electricity utility cost rate strategy (Benelmir and Fedit, 1998). On the other hand, it is necessary to manage energy systems based on environmental criteria to design sustainable technologies that minimize the global impacts resulting from systems' operation.

The complexity in operating cogeneration systems, especially when considering integrating them with conventional systems such as the electric grid and gas boilers, arises from the fact that there are many options to size and operate these systems, depending on their respective characteristics, as well as the energy use profile of a building. Cogeneration systems can be sized to meet the annual peak thermal or electric demand and can be operated to follow the thermal load of the building, the electric load of the building, or periodically adjusted to follow either the electric and thermal load depending on the objective of the user. Several of the studies relating to the application of combined heat and power (CHP) technologies were performed to investigate operational strategies mainly from the efficiency and economic perspectives (Arivalagan et al, 1995; Few et al, 1997; Fawkes et al, 1998; Jones, 1999; Brandon and Snoek, 2000; Gunes, 2001; Marantan et al, 2002; Jalalzadeh et al, 2002; Yodovard et al, 2001; Ellis and Gunes, 2002).

Operations Research (OR) techniques were used to optimize the operation of utility plants to minimize operating costs or to maximize revenue (O'Brien and Bansal, 2000). The focuses of the studies on cogeneration systems have been limited to gas and steam turbines (Marechal and Kalitventzeff, 1998; Venkatesh and Chankong, 1995); however, one study investigated the optimization of solid oxide fuel cell and gas turbine combined cycle with regards to cost and emission rates (Burer et al, 2003). Within those studies the environmental impacts that were addressed were limited to the assessment of the carbon dioxide emissions resulting from the operation of these systems (Chung et al, 1997; Wu and Rosen, 1999; and Burer et al, 2003).

The life cycle assessment (LCA) framework provides a tool to understand and analyze the performance of these energy systems by considering the different products' life stages and their impact on the environment (ANSI/ISO, 1997). The environmental impact can be global such as greenhouse gases, regional, such as acid rain, or local, such as smog formation. In addition, the efficiencies of these energy systems directly impact the consumption of primary energy resources. Therefore, in light of the necessity for the sustainable use of energy resources and cleaner environment, the understanding of the environmental impact associated with the production of energy and the application of these energy systems in buildings is important in building design.

Few LCA studies in the literature address the application of cogeneration systems in buildings. The LCA studies include the assessment of the environmental impacts resulting from various electric generation systems (Michaelis, 1998; Gagnon et al, 2002), natural gas combined cycle (NGCC) systems (Spath and Mann, 2000; Lombardi, 2003), and solid oxide fuel cell cogeneration system (Pehnt, 2003).

The model presented in this paper intends to optimize the selection and operation of energy systems based on their potential life cycle environmental impacts by integrating LCA and OR techniques. By using a hypothetical case study of a commercial office building, the analysis of the results showed that the model is appropriate for infrastructure decision support in both the design and operation of building energy systems. For design, the model can be used to determine energy system strategies. For design and evaluation of the operation phase, the model can be used to ascertain the most efficient operating strategy to be implemented based upon predicted energy use from hourly building energy simulation data. This improves system performance when compared to a fixed operating strategy such as when following the thermal or electric load of a building. The model could also be useful for making operational decisions when predictions of short-term expected loads are fairly well known. The model can also be used to assess alternative building energy use reduction efforts regarding electrical and thermal energy and to determine which alternative would have the best result for the effort invested. Lastly, the model can be used for single building energy systems or those that are designed to serve the energy requirements of multiple buildings in an area, such as campus or municipal energy systems.

2. APPROACH

A life cycle optimization model is developed in order to consider environmental performance in the design of building operations. The approach consists of the following stages:

- Energy simulation,
- Life cycle assessment and
- Optimization

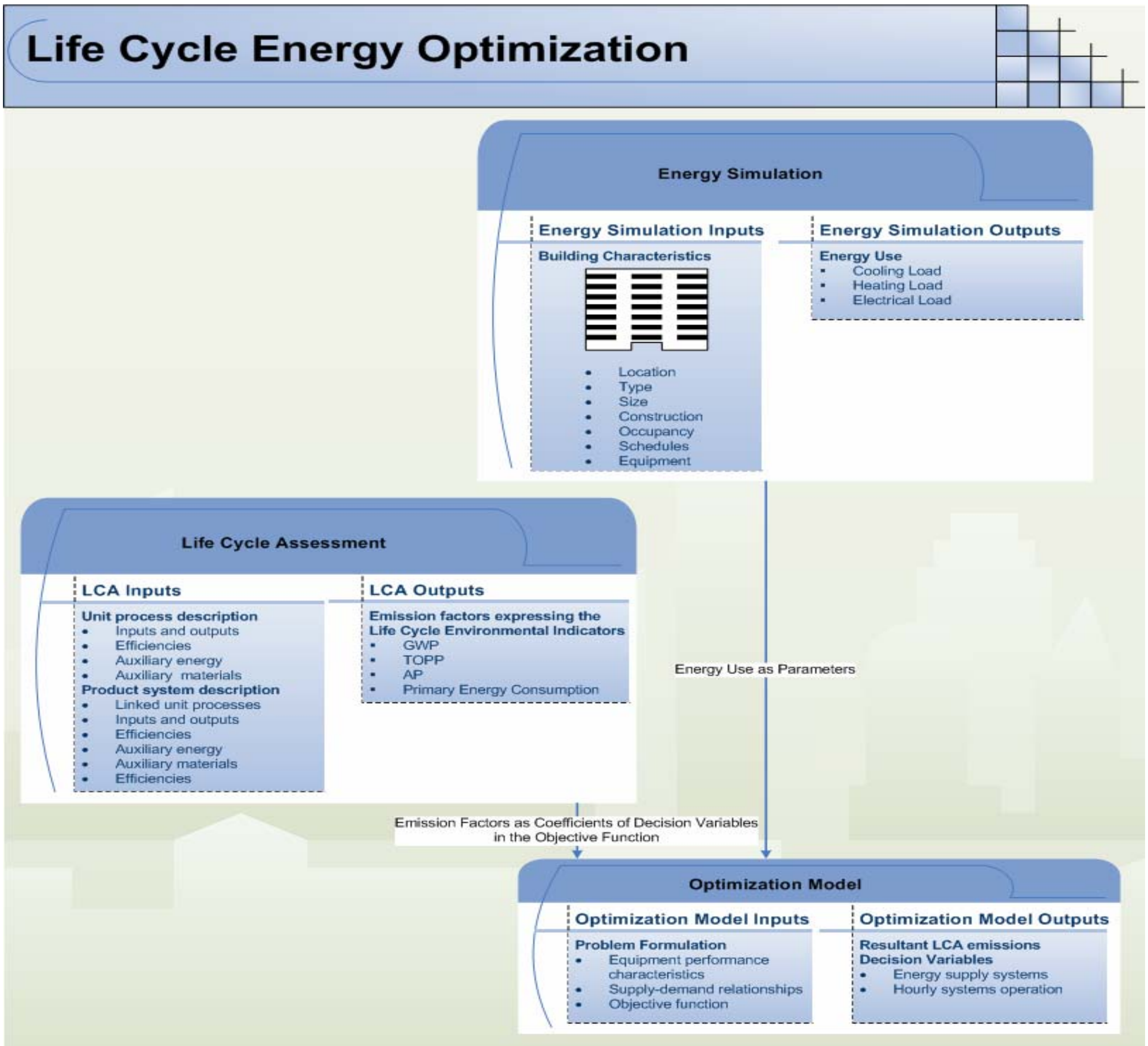

FIG. 1: Illustration of life cycle energy optimization model.

The first stage, energy simulation, is used to define the building's characteristics and determine the building energy use profile. The second stage, life cycle assessment, is used to develop energy systems models that are used in meeting the building's energy demand. The emissions results obtained from the LCA model are used as coefficients of the decision variables in the optimization model. The third stage, optimization, is used to determine the optimum energy systems and operational strategies used to meet building's energy demand. Depending on the user's objective, the optimization model could be used to achieve a single objective or a combination of objectives, such as minimizing primary energy consumption and emissions. Fig. 1 shows an illustration of the study approach.

2.1 Energy Simulation

Energy simulation is used to obtain the hourly heating, cooling, and electrical loads of a building. Energy simulation allows the user to define a number of building characteristics, such as:

- building geometry and construction materials,
- location with specific weather characteristics,
- building size,
- building use,
- specific occupancy characteristics,
- equipment use schedules and
- lighting use schedules.

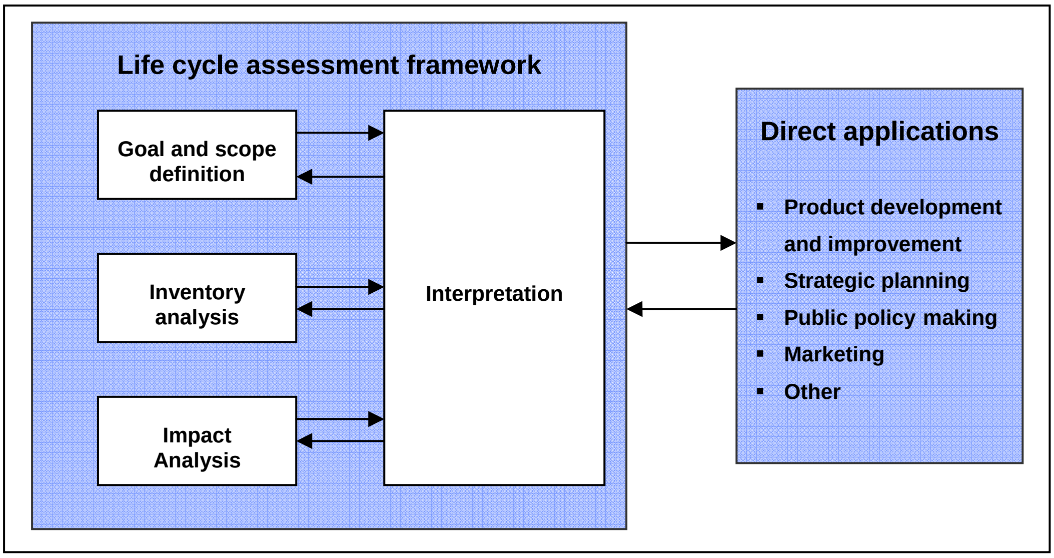

FIG. 2: Illustration of life cycle assessment framework (ANSI/ISO, 1997).

Energy simulation software is then used to generate the building hourly energy use that matches the building's characteristics as defined by the user. In addition, energy-efficient strategies can be defined, such as day-lighting with associated dimming of artificial lights, using energy-efficient lights, improving insulation throughout, improving windows, reducing infiltration, incorporating passive solar heating, shading windows, adding thermal mass, installing higher efficiency HVAC, relocating ducts to inside the thermal envelope, enhancing HVAC controls, and using an economizer cycle (SBIC, 1996). Energy use results can also be obtained in annually and monthly basis. There are a number of energy simulation software packages available that can be used to generate the electrical and thermal demand profiles at the required time step. Energy-10 (SBIC, 1996) has been used in the current model implementation. The hourly heating, cooling, and electrical loads of the building become parameters in the optimization model.

2.2 Life Cycle Assessment

The LCA model is developed following the International Organization for Standardization (ISO) framework (ANSI/ISO, 1997). LCA studies the environmental aspects and potential impacts throughout a product's life (i.e., cradle-to-grave) from raw material acquisition through production, use and disposal. According to the International Standards, the LCA phases include definition of goal and scope, inventory analysis, impact assessment, and interpretation, as shown in Fig. 2.

2.2.1 Goal of the study:

The goal of this study is to create LCA models for four types of building energy systems:

- grid-based energy systems,
- cooling systems,
- heating systems and
- cogeneration systems.

These models assess the life cycle environmental impact of the production of energy for buildings. The outputs of these models are also used in the optimisation model.

2.2.2 Scope of the study:

The scope of the study covers the following product systems:

Grid-based energy systems (two systems are modelled to supply electricity for a building):

1. US average electric grid: the electric generation mix in the US supplied by the grid is modelled as follows: 53% coal, 17% natural gas, 17% nuclear, 9% hydro, 2% oil, 2% waste, 0.4% geothermal and 0.15% wind (IEA, 1998). An average grid loss of 6.5% is considered in the process; the total efficiency of the electric generation process is 32% (EIA, 2002).
2. Natural gas combined cycle (NGCC): A 500-MW NGCC power plant with 49% electrical efficiency is used in the scenarios to represent the best available central generation technology. Specifications and assumptions are acquired from a life cycle assessment study of a natural gas combined cycle power generation system (Spath and Mann, 2000). The plant configuration consists of two gas turbines, a three pressure heat recovery steam generator, and a condensing reheat steam turbine. Natural gas is fed into a gas turbine which drives the generator. Waste heat from the turbine is captured by the heat recovery steam generator which provides steam for the steam turbine which in turn also drives a generator (Spath and Mann, 2000). In such a system, usually two thirds of the electric power is provided by the gas turbine and one third by the steam turbine (Hay, 2000). Emissions from the NGCC process are obtained from EPA's AP-42 emission factors for gas turbines (EPA, 1995).

Cooling systems (two systems are modelled to supply cooling for a building):

1. Absorption chiller (AC): A 1.5-MW two-stage absorption chiller uses water as the refrigerant and lithium bromide as the absorbent. The AC is driven by heat. Operation data from a commercially available absorption chiller, (York, 1997), is used to create the process model. Auxiliary energy required for the operation of the AC is supplied by U.S. average electric grid. The coefficient of performance (COP) of the AC is 1.05.
2. Electric chiller (EC): A 196-kW EC is modelled. Electric chillers provide chilled water for all air conditioning applications that use central station air handling or terminal units and are driven by electricity. Operation data from a commercially available absorption chiller (York, 1999), is used to create the process model. The COP of the EC is 4.6.

Heating systems: A 1-MW natural gas-fired boiler with efficiency of 88.7% is modeled to supply the required heating demand in a building. The emissions from the boiler are acquired from EPA’s AP-42 for gas boiler (EPA, 1995).

Cogeneration systems: three cogeneration systems are modelled to supply the electrical and/or thermal requirements of a building):

1. Microturbine (MT): The MT modelled is a 60-kWe natural gas-fired MT unit with 80% overall efficiency of fuel input, 28% of which is electrical and 52% is thermal. Process efficiencies and emissions at part load operations are also used in developing the microturbine model adapted from a Capstone microturbine (GHG, 2003). Microturbines are just emerging as a future distributed resource that will be ideally sized to meet the electric load profiles of many commercial and institutional end-users. They are mostly run on natural gas and exhaust heat can be recovered for hot water or steam loads.
2. Internal combustion engine (ICE): Commercially available reciprocating engines for power generation range from 0.5-kW to 6.5-MW. Different size ranges are modelled including process efficiencies and emissions at part load operations adapted from Caterpillar gas engines (Caterpillar Inc., 1999). Natural gas reciprocating engines are a popular choice for commercial combined heat and power applications due to their good part-load operation and availability of size ranges that match the load of many commercial and institutional end-users. System overall efficiency is about 88% of fuel input, 33% of which is electrical and 55% is thermal. Steam or hot water can be generated from recovered heat that is typically used for space heating, reheat, domestic hot water and absorption cooling.
3. Solid oxide fuel cell (SOFC): Another emerging technology for combined heat and power application is the SOFC. A 110-kWe SOFC with 80% overall efficiency of fuel input, 47% of which is electrical and 26-33% is thermal, is used in the model. The difference in thermal

efficiency between the 26% and 33% SOFC is that the 26%-thermal SOFC uses part of the generated heat to provide heat for the fuel reformation process. The SOFC process model is adapted from Siemens Westinghouse SOFC (Bessette et al, 2001). Natural gas is reformed to hydrogen gas without loss. With exhaust temperature of up to 600°F, steam or hot water can be generated from recovered heat that is typically used for space heating, reheat, domestic hot water and absorption cooling.

2.2.3 Functional units and system boundaries

The functional unit: The functional unit is a measure of performance of the functional outputs of the product system. The primary purpose of a functional unit is to provide a reference to which the inputs and outputs are related (ANSI/ISO, 1997). The functional unit used in this study is 1-kWh of energy consumption.

The product system boundaries: The system boundaries determine which unit processes shall be included within the LCA (ANSI/ISO, 1997). System boundaries considered in this study are: elementary flow at system boundaries and the defined technology specifications. Fig. 3 shows a schematic of a typical product system used in developing the LCA model.

2.2.4 Life cycle inventory analysis

The inventory analysis involves data collection and calculation procedures to quantify relevant inputs and outputs of the product system. These data also constitute the input to the life cycle impact assessment (ANSI/ISO, 1997). The major product systems constituting the production and use of energy generation investigated in this study include unit processes that are linked to one another by product flows across the systems boundaries, such as energy flow, intermediate product flows within the systems boundaries, such as auxiliary energy flow, and elementary flows to the environment, entering a unit process, such as natural gas or leaving a unit process, such as air emissions and water effluents.

LCA software, Global Emission Model for Integrated Systems (GEMIS) (Fritsche and Schmidt, 2003), is used to design the LCA models and generate the emissions resulting from the production and use of energy in the case building under study. In addition, GEMIS database is used in modelling the upstream processes, such as fuel and material exploration, production, and distribution. In developing the LCA model, processes are defined which converts, transports, or produces a product, for example a resource, such as natural gas is converted to electricity by linking all the processes involved in the extraction, transportation, and conversion to electricity.

2.2.5 Life cycle impact assessment

The impact assessment step of the LCA evaluates the significances of potential environmental impacts using the results of the life cycle inventory analysis. The environmental impact indicators chosen to quantify the potential contribution of the products' inventory flow are:

- Primary Energy Consumption,
- Global Warming Potential (GWP),
- Tropospheric Ozone Precursor Potential (TOPP) and
- Acidification Potential (AP).

Primary energy consumption is a quantitative measure of the total amount of primary energy resources needed to deliver energy. Resources are products that can be converted to energy carriers e.g. oil and coal from which fuels can be derived, wind, hydro-power etc. This impact addresses only the depletion effect of resource extraction, i.e. the upper end of the process chains, and not impacts resulting from extraction processes, such as emissions. The impact of primary energy use determines the availability of natural resources, which translates to issues such as efficiency, conservation, sustainable energy use, etc.

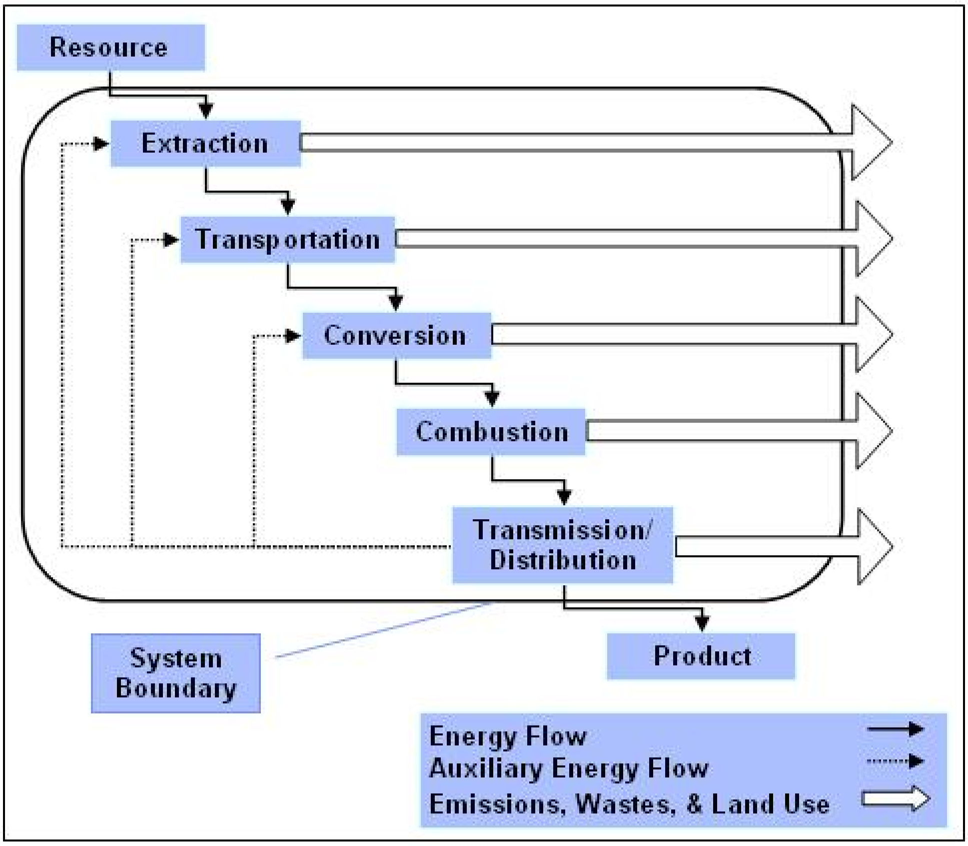

FIG. 3: Energy flow in a typical product system

GWP is the mass-based equivalent of the radiative forcing of green house gases (GHG), based on the specific forcing of CO_2. It is expressed in CO_2 equivalents. Because GHG, such as methane and carbon dioxide, have different atmospheric residence times, the GWP is determined as an integral over a period of time; usually, GWP data refer to a time horizon of 100 years. Although trends in levels of the GHG are well known, their effects on global temperature and climate are much less certain. Most computer models predict global warming of 1.5-5 °C; such warming would have profound effects on rainfall, plant growth, and sea levels which might rise as much as 0.5-1.5 meters (Manahan, 1994).

TOPP is the mass-based equivalent of the ozone formation rate from precursors, measured in ozone precursor equivalents. The TOPP represents the potential formation of near-ground (tropospheric) ozone which can cause summer photochemical smog. Although not a great threat to the global atmosphere, smog does pose significant hazards to living things and materials in local urban areas. Ozone, which serves an essential protective function in the stratosphere, is the major cause in the tropospheric smog. Surface ozone levels are used as a measure of smog. Ozone photo toxicity raises a particular concern in respect to trees and crops. In addition, ozone is responsible for most of the human respiratory system distress and eye irritation resulting from exposure to smog, for instance, breathing is impaired at ozone levels at about 0.1 ppm (Manahan, 1994).

Acidification potential (AP) is the result of aggregating acid air emissions, expressed in SO_2 equivalents. The SO_2 equivalents express the acidification potential (AP) and are calculated from the molecular weights and the proton binding potential of the respective emissions (by definition AP is equal to one for SO_2). Acid rain spreads out over several hundred to several thousand kilometres; this classifies it as a regional air pollution problem compared to a local air pollution problem, smog, or a global one, such as greenhouse gases. Emissions from industrial operations and fossil fuel combustion are the major sources of acid-forming gases. Some of the impacts of acid rain are: direct phytotoxicity to plants from excessive acid concentrations, destruction of sensitive forests, respiratory effects on humans and animals, acidification of lake water with toxic effects to lake-flora and fauna, and corrosion to exposed structures, electrical relays, equipment, and ornamental materials especially those made of limestone (Manahan, 1994).

The following environmental impact indicators, GWP, TOPP, and AP equivalents, are calculated as follows:

$$Indicator_{equivalence} = \sum \left[e_i \times Indicator_i \right] \quad (1)$$

where,

e_i = mass of emission (i) in kg, and

$Indicator_i$ = environmental impact indicator of emission (i), in [kg/kg]

Table 1 shows the emission equivalents that express GWP, TOPP, and AP.

Life cycle (LC) emission factors are representative values that attempt to relate the quantity of a pollutant released to the atmosphere with an activity associated with the release of that pollutant. In this study, the emission factors are expressed as the weight of the pollutant in terms of the environmental impact indicators divided by a unit (kWh) consumed. These emission factors are then used as coefficients of the decision variables in the objective function of the optimization model.

2.3 Optimization

2.3.1 Model Description

The optimization model developed in this study allows for integrating cogeneration systems with a grid-based electric generation systems, as well as, heating and cooling systems. The optimization model results in a mixed integer linear programming (MILP) problem. When solved, the values of the decision variables represent the optimum operational strategy according to a linear objective function subject to the specified constraints.

Variables are composed of continuous and binary variables. Continuous decision variables are used in the formulation of equipment performance characteristics, energy balance, and supply-demand relationships. Binary variables (0-1 variables) are used to determine if a particular cogeneration unit is used at a certain time or not. The binary variables also ensure that the selected cogeneration unit will only operate at a particular part load level at a certain time.

Linear equations are used to formulate the constraints describing the correlations between the capacities and efficiencies of energy systems corresponding to their rated and part load operation. The objective function of the optimization problem is formulated by using continuous decision variables for energy supply and the emission factors as coefficients of the variables for the energy systems considered. Table 2 shows the parameters and decision variables used in the formulation of the optimization model.

2.3.2 Objective Function

The objective function is formulated to minimize the total LC emissions expressed in *kg* (e.g. *kg of* CO_2 *equivalents* when minimizing LC GWP). The LC emissions include the emissions from the life cycle of the processes from resource extraction, production, and operation.

$$Minimize \sum_{h=1}^{24} \left\{ \left[P\_GRID_h \times EF\_GRID \right] + \left[\sum_{u=1}^{n} \sum_{p \in P} COGEN_{uph} \times EF\_COGEN_{up} \right] + \left[H\_B_h \times EF\_BOILER \right] \right\} \quad (2)$$

TABLE 1:Emission equivalents for CO_2 (IPCC, 1996-a), TOPP (EEA, 2000), and SO_2 (EEA, 2000).

Emission Equivalents	CO_2	CH_4	N_2O	NOx	NMVOC	CO	SO_2	HCL
CO_2 equivalents	1	21	316	-	-	-	-	-
TOPP equivalents	-	0.014	-	1.22	1.0	0.11	-	-
SO_2 equivalents	-	-	-	0.696	-	-	1.0	0.878

TABLE 2: Parameters and decision variables for optimization model.

Parameters	Description
h	Index number for operating hours, $h = 1, 2, ..., 24$.
p	Index number for part load operating level of a particular cogeneration unit. For MT units $p = 25, 50, 75, 100$ and for the ICE units $p = 50, 75, 100$.
u	Index number for cogeneration units, $u = 1, 2,..., n$, where n is the total number of cogeneration units.
C_h	Cooling required for space cooling at hour h.
$COGEN\_MaxCap_{uph}$	The maximum electric generation capacity from a cogeneration unit u operating at part load level p at hour h.
$COGEN\_MinCap_{uph}$	The minimum electric generation capacity from a cogeneration unit u operating at part load level p at hour h.
EF_BOILER	LC emission factor resulting from generating *1-kWh* of thermal energy from a gas boiler.
EF_COGEN_{up}	Life Cycle (LC) emission factor resulting from a cogeneration unit u operating at part load level p to generate *1-kWh* of electric energy.
EF_GRID	LC emission factor resulting from obtaining *1-kWh* of electricity from the grid.
H_h	Heating required for space and water heating at hour h.
P_h	Power required for miscellaneous electric demand, other than cooling, at hour h.
PH_RATIO_{up}	Power to heat efficiency ratio of a cogeneration unit u operating at part load level p.
Decision Variables	
C_AC_h	Cooling obtained from the absorption chiller at hour h.
C_EC_h	Cooling obtained from the electric chiller at hour h.
$COGEN_{uph}$	Binary variable for cogeneration unit u operating at part load level p at hour h, $\begin{cases} 1 & \text{if unit is in use} \\ 0 & \text{otherwise} \end{cases}$
H_AC_h	Heating required to drive the absorption chiller to supply the cooling demand at hour h.
H_B_h	Heating obtained from the gas boiler at hour h.
H_COGEN_{uph}	Heat obtained from cogeneration unit u operating at part load level p at hour h.
H_EXCESS_h	Excess heat remaining after all the heating requirements are met at hour h.
P_COGEN_{uph}	Power obtained from cogeneration unit u operating at part load level p at hour h.
P_EC_h	Power required to drive the electric chiller to supply the cooling demand at hour h.
P_EXCESS_h	Excess power remaining after all the power requirements are met at hour h.
P_GRID_h	Power obtained from the grid at hour h.

2.3.3 Constraints:

Energy balance and supply-demand

The building's power demand consisting of power required for miscellaneous office equipment and lights, and power required for cooling if an electric chiller is used, must be satisfied each hour. Each hour, power can be supplied by the grid and/or specific cogeneration unit(s) operating at a particular load.

$$P\_GRID_h + \sum_{u=1}^{n} \sum_{p \in P} P\_COGEN_{uph} \geq P_h + P\_EC_h \tag{3}$$

The building's thermal demand, consisting of thermal energy required for space and water heating, and thermal energy required for cooling if an absorption chiller is used, must be satisfied each hour. At a particular hour, thermal energy can be supplied by a gas boiler and/or specific cogeneration unit(s) operating at a particular load.

$$H\_B_h + \sum_{u=1}^{n} \sum_{p \in P} H\_COGEN_{uph} \geq H_h + H\_AC_h \tag{4}$$

The building's cooling demand must be satisfied each hour. At a particular hour cooling can be supplied by an absorption chiller and/or an electric chiller.

$$C\_AC_h + C\_EC_h = C_h \qquad (5)$$

The hourly excess electrical energy is defined as:

$$P\_EXCESS_h = \left\{ \left[P\_GRID_h + \sum_{u=1}^{n} \sum_{p \in P} P\_COGEN_{uph} \right] - \left[P_h + P\_EC_h \right] \right\} \qquad (6)$$

The hourly excess thermal energy is defined as:

$$H\_EXCESS_h = \left\{ \left[H\_B_h + \sum_{u=1}^{n} \sum_{p \in P} H\_COGEN_{uph} \right] - \left[H_h + H\_AC_h \right] \right\} \qquad (7)$$

Performance characteristics of energy systems

Each hour, the electric energy generated from a cogeneration unit operating at a particular part load level is equal to the product of the thermal energy required by the unit and the power to heat ratio of that unit.

$$P\_COGEN_{uph} = H\_COGEN_{uph} \times PH\_RATIO_{up} \qquad (8)$$

Each hour, the electric energy obtained from a cogeneration unit operating at a particular part load level is greater than or equal to the minimum capacity of that unit and less than or equal to the maximum capacity of that unit.

$$\begin{aligned} P\_COGEN_{uph} &\geq COGEN\_MinCap_{uph} \times COGEN_{uph} \\ P\_COGEN_{uph} &\leq COGEN\_MaxCap_{uph} \times COGEN_{uph} \end{aligned} \qquad (9)$$

Each hour, the cooling energy obtained from an absorption chiller is equal to the product of the thermal energy required and the coefficient of performance (COP) of the absorption chiller.

$$C\_AC_h = H\_AC_h \times AC_{COP} \qquad (10)$$

Each hour, the cooling energy obtained from an electric chiller is equal to the product of the electric energy required and the COP of the electric chiller.

$$C\_EC_h = P\_EC_h \times EC_{COP} \qquad (11)$$

3. ASSUMPTIONS AND LIMITATIONS

Main assumptions made in the study are:

- Thermal and electric conversion efficiencies of the cogeneration systems are achievable.
- Cogeneration systems are capable of following a specific thermal or electrical load of the building.
- The thermal and electric energy produced from a cogeneration process is of utilizable quality.
- No heat or electric loses from a cogeneration process are considered other than those captured by the conversion efficiencies.
- No credit is taken for any electrical energy generated above the demand.

Some of the limitations of this study are:

- The current study is a hypothetical case which might not apply to real world scenario.
- Environmental impact indicators used in this study are not representative of comprehensive environmental impact analysis but represent a class of widely used environmental parameters, which could be used for comparative analysis with previous and future studies. A comprehensive environmental impact analysis, including economic impacts, would be more valuable if the study was done on an actual setting; however, because the current study is done on a hypothetical building, the results could provide a general understanding of the performance of energy systems in buildings and ways to minimize the environmental impacts of their use. Some of the principal environmental impact indicators not addressed in this study are economic impacts, human toxicity, ecological toxicity, particulates formation and indoor air quality.

- Economic implications are not considered in the analysis. Cost analysis is not performed at this stage of the study, which is a key determinant in real world application of cogeneration systems.

4. CASE STUDY

4.1 Problem Formulation

The case building is a 100,000 square foot commercial office building. The climate chosen has average cooling degree days (CDD) less than 2000 and heating degree days (HDD) less than 5500. Design characteristics for the case building are based on U.S. average construction data obtained from the literature (Sezgan et al, 1995). Some of the main building characteristics are:

- Wall materials: 8-inch masonry, rigid insulation, and gypsum board,
- Roof construction: flat, build-up roofing, rigid insulation, and gypsum board ceiling and
- Windows: double glazed with aluminium frames

In this paper, energy use for the case building is presented for a typical day in August. The thermal load of the building consists mainly of domestic water heating, the electric load consists of electricity required for miscellaneous electric equipment and lighting. Cooling demand can be added to the thermal load if an absorption chiller is used or can be added to the electric load if an electric chiller is used. Thermal and electrical energy storage systems are not considered.

The optimization model considers ten 60-kWe MT units, average electric grid power, a gas boiler, and absorption and electric chillers. Each MT unit is modeled to operate at four part load levels: 25%, 50%, 75%, and 100% load. Another problem is formulated to present a base case scenario representing conventional practice, where the only source for electricity is the electric grid, the heating source is the gas boiler, and cooling can be supplied by the AC and/or EC.

The performance characteristics of the MT unit are given in Table 3. The efficiency of the average electric grid is 32% and the coefficient of performance (COP) of the AC is 1.05, and the COP of the EC is 4.6. The emission factors of the energy systems obtained from the LCA model are given in Table 4.

TABLE 3: Efficiencies of MT.

	Electrical Efficiency %				**Thermal Efficiency %**				**Overall Efficiency %**			
Part Load	***100%***	***75%***	***50%***	***25%***	***100%***	***75%***	***50%***	***25%***	***100%***	***75%***	***50%***	***25%***
60-kW MT	28	24.2	20.0	13.1	52	56.4	56.7	58.0	78.4	80.7	76.7	71.1

TABLE 4: Emission factors of energy systems.

System	**Electric Grid**	**Gas Boiler**	**MT**	**MT**	**MT**	**MT**
Part Load			***100%***	***75%***	***50%***	***25%***
PEC [kWh/kWh of energy use]	3.09	1.18	3.99	4.32	5.22	7.97
TOPP [kg TOPP Equiv./kWh]	0.0035	0.00021	0.00083	0.00081	0.0064	0.0038
GWP [kg CO_2 Equiv./kWh]	0.787	0.254	0.749	0.795	1.067	1.479

In this example two optimization problems are presented. The first optimization problem is formulated with the objective to achieve minimum LC primary energy consumption expressed in *kWh*. The second optimization problem is formulated with the objective to achieve minimum LC TOPP expressed in *kg of ozone precursor potential*. The third optimization problem is formulated with the objective to achieve minimum LC GWP expressed in *kg of carbon dioxide equivalent.*

4.2 Discussion and Results

4.2.1 First Optimization Problem: minimize total LC primary energy consumption.

The total minimum LC primary energy consumption (PEC) in a typical day in August is found to be 15579 kWh. The optimum operational strategies are found to be: MT units operating at full load are used to supply power primarily and partially power is obtained from the grid during some hours. Refer to Fig. 4. During all hours of the day, cogenerated heat from the MT units is used to meet the heating requirements of the building and the rest of the heat is used for cooling with AC. Refer to Fig. 5. Cooling is met primarily by AC driven by heat from MT and partially by EC during peak hours, refers to Fig. 6.

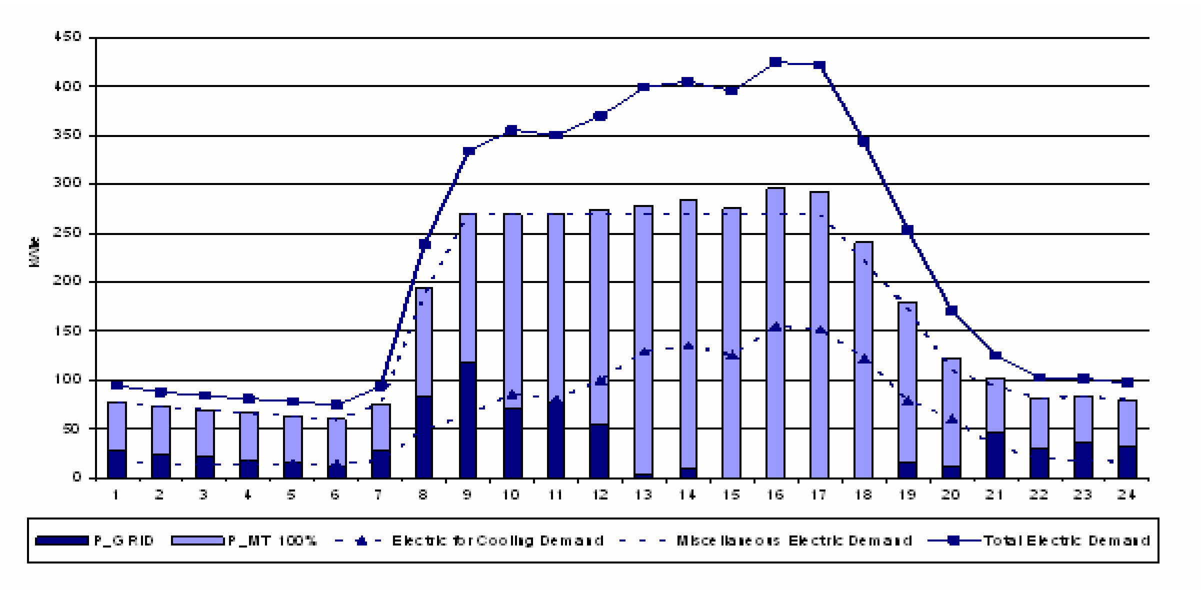

FIG. 4: Power generation during a typical day in August for minimum PEC.

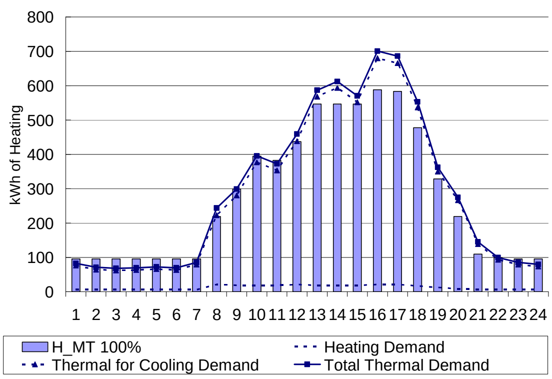

FIG. 5: Thermal energy generation during a typical day in August for minimum PEC.

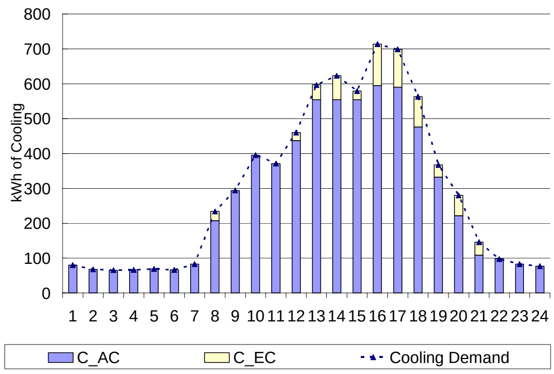

FIG. 6: Cooling energy generation during a typical day in August for minimum PEC.

In the base case scenario, the total minimum LC primary energy consumption in a typical day in August is found to be 15759 kWh. Electricity is supplied by the electric grid, heating by the gas boiler, and cooling by the electric chiller. When comparing the results from the MT optimization problem to the results from the base case scenario, there is no significant decrease in primary energy consumption, however, the operation strategies were considerably different showing the sensitivity of the model towards optimizing energy use by minimizing the LC primary energy consumption.

4.2.2 Second Optimization Problem: minimize total LC TOPP

The total minimum LC TOPP in a typical day in August is found to be *three kg of ozone precursor potential*. The optimum operational strategies are found to be: MT units operating at 75% and 100% load are used to supply power during all hours of the day. Refer to Fig. 7. The cogenerated heat from the MT units is used to meet the heating requirements of the building and the rest of the heat is used for cooling with AC. Refer to Fig. 8. Cooling is met primarily by AC driven by heat from MT and partially by EC during peak hours, refer to Fig. 9. No power is obtained from the grid at any time.

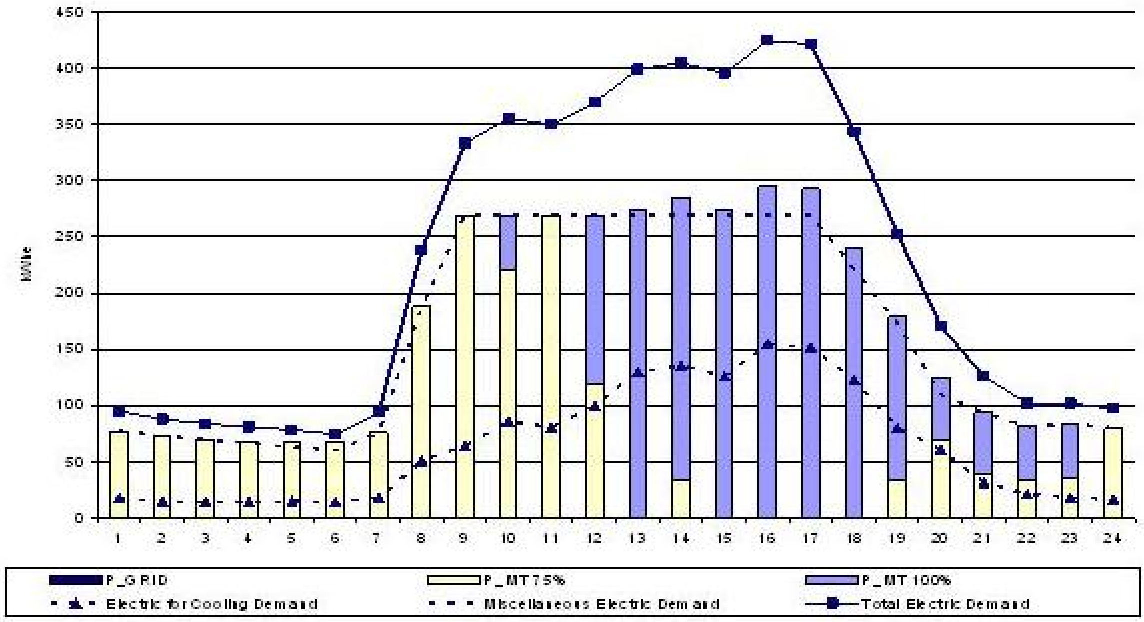

FIG. 7: Power generation during a typical day in August for minimum TOPP.

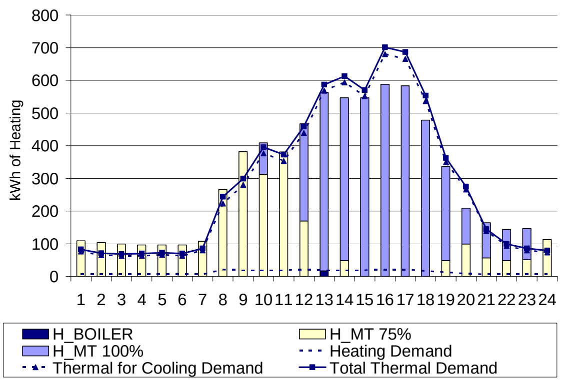

FIG. 8: Thermal energy generation during a typical day in August for minimum TOPP.

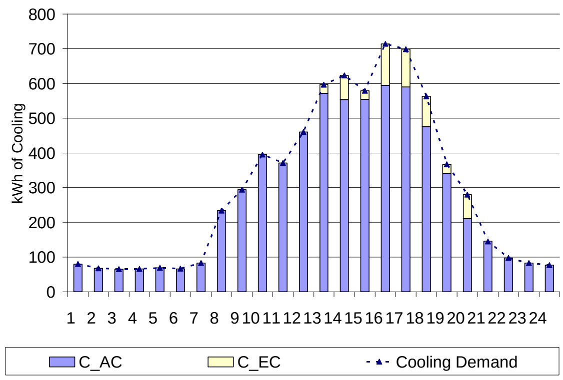

FIG. 9: Cooling energy generation during a typical day in August for minimum TOPP.

In the base case scenario, the total minimum LC TOPP is *13 kg of ozone precursor potential*. Electricity is supplied by the electric grid, heating by the gas boiler, and cooling by AC driven by heat from the gas boiler. When comparing the results from the MT optimization problem to the results from the base case scenario, it is found that 77% reduction in ozone precursor potential can be achieved by using MT cogeneration system instead of conventional systems.

4.2.3 Third Optimization Problem: minimize total LC GWP

The total minimum LC GWP in a typical day in August is found to be *3043 kg of carbon dioxide equivalent*. The optimum operational strategies are found to be: MT units operating at 100% load are used to supply power during most operating hours of the day (Hour 7-20) and partial power is obtained from the grid during the rest of the day. The cogenerated heat from the MT units is used to meet the heating requirements of the building and the rest of the heat is used for cooling with AC. Cooling is met primarily by AC driven by heat from MT and partially by EC during peak hours.

In the base case scenario, the total minimum LC GWP is 3998 kg of *carbon dioxide equivalent*. Electricity is supplied by the electric grid, heating by the gas boiler, and cooling by EC. When comparing the results from the MT optimization problem to the results from the base case scenario, it is found that 24% reduction in GWP can be achieved by using MT cogeneration system instead of conventional systems.

In addition, results are found to vary according to the user's objectives. Hence, when designing energy systems, a holistic approach should be taken to investigate different parameters in order to optimize system selection with the minimum environmental impacts. In this example, tradeoffs are seen between using microturbine cogeneration system as opposed to conventional systems. This approach can help the decision maker in designing energy systems in commercial buildings that would reduce environmental impacts such as GWP and TOPP rather that only economical implications.

Results show that this model is applicable in the selection and operation of cogeneration systems while integrating them with grid-based electricity, gas boiler, and absorption and electric chillers. Also, the MILP is useful for optimization with respect to environmental criteria rather than merely economical objectives, which is important in designing sustainable energy systems for buildings. The model is currently being augmented to consider not only environmental but also capital, maintenance, and operational costs of these energy systems which will impact the results, especially the number of units selected for operation.

5. CONCLUSION

In this paper an LCA optimization model is presented which uses environmental criteria for the selection of energy systems and optimization of the operational strategies that integrate cogeneration systems with utility energy systems in commercial building applications. Such an approach could be used for sustainable planning when designing for optimum energy management in buildings by considering lower primary energy consumption, and emissions while maximizing processes efficiencies. The LCA optimization model will be useful for:

- Selecting energy systems for building applications,
- Designing operational strategies while considering system's characteristics, such as efficiencies, capacities, and emissions, as well as variable loads of buildings,
- Analyzing the effects of various thermal and electrical energy use in buildings on the performance of energy systems,
- Control of energy systems in operation and
- Predicting the environmental life cycle impact resulting from the life cycle of a building's energy systems.

Given resource constraints and pollution generation from building energy systems, a model that can be used in decision making regarding the optimization of impacts from building energy use can be a valuable tool for infrastructure management.

6. REFERENCES

A.D. Little. (2000). Opportunities for Micropower and Fuel Cell/Gas Turbine Hybrid Systems in Industrial Applications. *Rep. No. 38410*, Vol.1: Main Text. Cambridge, MA.

ANSI/ISO. (1997). Environment Management-Life Cycle Assessment-Principles and Framework, *14040-1997*, NSF International, Ann Arbor, MI.

Arivalagan A., Raghavendra B.G., and Rao A.R.K. (1995). Integrated energy optimization model for a cogeneration based energy supply system in the process industry, *Electrical Power & Energy Systems*, Vol. 17, No. 4, 227-233.

Benelmir R. and Feidt M. (1998). Energy Cogeneration Systems and Energy Management Strategy. *Energy Conversion and Management*, Vol. 39, No. 16-18, 1791-1802.

Bessette N.F., Borglum B.P., Schichl H., and Douglas D.S. (2001). Siemens SOFC Technology on the way to economic competitiveness. *Siemens Power Journal*. <http://www.siemenswestinghouse.com> (July 25, 2002).

Brandon P. and Snoek C. (2000). Microturbine Cogeneration. *ASHRAE Transactions*, Vol. 106, No. 1, 669-74.

Burer M., Tanaka K., Favrat D., and Yamada K. (2003). Multi-criteria optimization of a district cogeneration plant integrating a solid oxide fuel cell-gas turbine combined cycle, heat pumps and chillers. *Energy*, Vol. 28, 497-518.

Caterpillar Inc. (1999). Gas engine technical data: G3304 NA. <http://www.caterpillar.com> (September 25, 2004).

Chung W., Wu J., and Fuller J.D. (1997). Dynamic energy and environment equilibrium model for the assessment of CO_2 emission control in Canada and the USA. *Energy Economics*, Vol. 19,103-124.

Ellis M.W. and Gunes M. (2002). Status of Fuel Cell Systems for Combined Heat and Power Applications in Buildings. *ASHRAE Transactions*, Vol. 108, No. 1, 1032-1044.

EIA (2002). Monthly Energy Review April 2002. Energy Information Administration <http://www.eia.doe.gov> (May, 2002).

EIA (2004). Emissions of Greenhouse Gases in the United States 2004. December 2005. Energy Information Administration Office of Integrated Analysis and Forecasting, U.S. Department of Energy, Washington, DC. <http://www.eia.doe.gov> (January, 2006).

EPA (1995). Compilation of air pollutant emission factors. AP-42: Stationary Point and Area Sources, 5th ed., Vol. 1, Research Triangle Park, N.C., Environmental Protection Agency <http://www.epa.gov/ttn/cheif/ap42> (May 15, 2002).

EEA (2000). Environmental Signals 2000. *Regular Indicator Rep*., European Environmental Agency, Copenhagen, Denmark.

Fawkes S.D., Jacques J.K., Linnell C., and Watkins A.A. (1998). Practical Modeling of Micro Combined Heat and Power Applications for Local Authority District Heating Schemes. *International Journal of Energy Research*, Vol.12, 611-629.

Few P.C., Smith M.A., and Twidell J.W. (1997). Modelling of a Combined Heat and Power (CHP) Plant Incorporating a Heat Pump for Domestic Use. *Energy*, Vol. 22, No. 7, 651-659.

Fristche U.R. and Schmidt K. (2003). Gemis Manual, Institute of Applied Ecology, Darmstadt, Germany.<http://www.oeko.de/service/gemis/en/g4_manual1.pdf> (January 15, 2004).

Gagnon L., Belanger C., and Uchiyama Y. (2002) Life Cycle Assessment of Electricity Generation Options: The Status of Research in Year 2001. *Energy Policy*, Vol. 30, 1267-78.

GHG (2003). Environmental Technology Verification Report: Combined Heat and Power at a Commercial Supermarket-Capstone 60 kW Microturbine CHP System. Chatsworth, CA., Greenhouse Gas Technology Center Research Institute , <http://www.epa.gov/etv> (June 10, 2004).

Gunes M. (2001). Investigation of a Fuel Cell Based Total Energy System for Residential Applications. MS Thesis, Dept. of Mechanical Engineering, Virginia Polytechnic Institute and State University, Blacksburg, VA.

Hay N.E. (1988). *Guide to Natural Gas Cogeneration.* USA: The Fairmont Press.

IEA (1998). *World energy outlook: Electricity information*, IEA Books, International Energy Agency, Paris.

IPCC (1996). *Climate change 1995. The science of climate change*, J. T. Houghton, L. G. Meiro Filho, B. A. Callander, N. Harris, A. Kattenberg and K. Maskell, eds., Intergovernmental Panel on Climate Change, Cambridge Univ. Press, Cambridge, U.K.

IPPC (2001). *Intergovernmental Panel on Climate Change, Climate Change 2001: The Scientific Basis*. Cambridge University Press, Cambridge, UK. (www.ipcc.ch)

Jalalzadeh-Azar A., Slayzak S., and Ryan J. (2002). Evaluation of Cooling, Heating, and Power (CHP) for Office Buildings. *ASHRAE Transactions*, Vol. 108, No. 1, 1045-1051.

Jones S. (1999). Micro-cogeneration Optimal Design for Service Hot Water Thermal Loads. MS Thesis, Dept. of Mechanical Engineering. Georgia Institute of Technology, Atlanta.

Lombardi L. (2003). Life cycle assessment comparison of technical solutions of CO_2 emissions reductions in power generation. *Energy Conversion and Management*, Vol. 44, No. 1, 93-108.

Manahan S.E. (1994). *Environmental Chemistry*, CRC Press LLC, USA.

Marantan A., Popovic P., and Radermacher, R. (2002). The Potential of CHP Technology in Commercial Buildings-Characterizing the CHP Demonstration Building. *ASHRAE Transactions*, Vol. 108, No. 1, 1025-1031.

Marechal F. and Kalitventzeff B. (1998). Process integration: Selection of the optimal utility system. *Computers Chem. Engng*., Vol. 22, Suppl., S149-S156.

Michaelis P. (1998). Life Cycle Assessment of Energy Systems. <http://www.rcep.org.uk/studies/energy/98-6067/michaelis.htm> (May 3, 2002).

O' Brien J. M. and Bansal P. K. (2000). Modelling of cogeneration systems Part 1: historical perspective, *Proc. Of the Institution of Mechanical Engineers*, Vol. 214, Part A, 115-124.

Osman A. and Ries R. (2004). Life Cycle Impact Analysis of Energy Systems in Buildings. *Journal of Infrastructure Systems,* 10 (3), 87-97.

Pehnt M. (2003). Life Cycle Analysis of Fuel Systems Components. *Handbook of fuel cells-fundamentals, technology and applications,* W. Vielstich, A. Lamm, and H. A. Gasteiger, eds., Wiley, Chichester, U.K., 1293-1317.

Sezgan O., Franconi E.M., Koomey J.G., Greenberg S.E., Afzal A., and Shown L. (1995). Technology data characterizing space conditioning in commercial building: Application to end-use forecasting with Commend 4.0. *Energy Analysis Program*, Ernest Orlando Lawerance Berkeley National Laboratory, University of California, Berkeley, Calif.

Spath P. and Mann M. (2000). Life Cycle Assessment of a Natural Gas Combined-Cycle Power Generation System. U.S. Dept. of Energy, Office of Scientific and Technical Information, Oak Ridge, Tenn.

SBIC (1996). Designing low energy buildings: Passive solar strategies and Energy-10 software. Sustainable Buildings Industry Council, Washington, D.C.

U.S. DOE (2003). *Annual Energy Review 2003*, Energy Information Administration, DOE/EIA-0384, Department of Energy, Washington, D. C.

Venkatesh B. and Chankong V. (1995). Decision Models for Management of Cogeneration Plants, *IEEE Transactions on Power Systems*, Vol. 10, No. 3, 1250-1256.

Wu J.Y. and Rosen A.M. (1999). Assessing and optimizing the economic and environmental impacts of cogeneration/district energy systems using an energy equilibrium model. *Applied Energy*, Vol. 62, 141-154.

Yodovard P., Khedari J., and Hirunlabh J. (2001). The Potential of Waste Heat Thermoelectric Power Generation from Diesel Cycle and Gas Turbine Cogeneration Plants. *Energy Sources*, Vol. 23, 213-224.

York (1997). Millennium YPC Two Stage Direct-Fired Absorption Chiller-Heaters. York International Corporation, York, PA, USA. <http://www.york.com> (March, 2002).

York. (1999). Liquid Chillers: Water Cooled Chiller and Remote Condenser Models. York International Corporation , York, PA, USA. <http://www.york.com> (March, 2002).