SIMULATION OF ENVIRONMENTAL IMPACTS OF COMMERCIAL BUILDING SYSTEMS

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ABSTRACT

Hourly energy simulation was used in combination with a life cycle assessment framework to model the environmental effects of energy consumption in buildings. The energy efficiencies and environmental impacts resulting from the construction and operation of alternative technnologies for providing space and water heating, cooling, and electrical power for equipment and lights in commercial buildings is evaluated. The analysis shows that building load characteristics are one of the main factors affecting the selection of technologies and operational strategies to limit the environmental impacts of building energy systems.

INTRODUCTION

The Energy Information Administration (EIA) of the Department of Energy estimates that commercial buildings in the United States consume 5.6 EJ of energy for space and water heating, cooling, and lighting, of which 2.1 EJ is natural gas (about 37%) (USDOE 1995). In addition, commercial buildings consume 2.5 EJ of electricity that results in 8.3 EJ of primary energy use, 0.2 EJ in fuel oil, and 0.6 EJ in district heating. This results in a total annual energy expenditure of $70 billion. The EIA also estimates that 92% of future generation capacity, including distributed generation, will be fueled with natural gas, and that distributed generation and fuel cells are expected to represent 3.5% of new generation capacity added by 2020 (EIA 2000). In commercial buildings in the United States, natural gas is recognized as the principal fuel for space and water heating, with electricity, principally generated off-site, used for cooling loads, lighting needs, and equipment. However, natural gas-fired equipment can also be used for on–site power generation in buildings. On–site generation is often co–generation, the combined production of both electrical (or mechanical) energy and thermal energy. Two–thirds of the primary energy used by conventional electric power plants is lost, largely as heat. In contrast, co–generation systems, or combined heat and power (CHP), recapture much of the otherwise wasted thermal energy and use this energy for a variety of purposes, such as space or water heating. Gas-fired cogeneration systems are an attractive option from both an environmental and an energy efficiency standpoint. On–site co–generation could make natural gas the dominant primary energy source for commercial buildings in the United States.

The analysis of the results from the current study demonstrated a) a framework that supports decision–making regarding system selection and operational strategies to limit environmental impact; b) the importance of a life cycle assessment framework, illustrated by the analysis of primary energy use, global warming potentials, acidification potentials, and tropospheric ozone potential; and c) the importance of building load characteristics for the analysis of CHP scenarios.

SIMULATION AND LIFE CYCLE ASSESSMENT

Study Description

The goal of this study was to evaluate natural gas-fired technologies for heating, cooling, and electrical energy generation in commercial buildings and compare these systems based on their primary energy consumption and emissions. The natural gas-fired cogeneration technologies studied were solid oxide fuel cell (SOFC), microturbine, and internal combustion engine (ICE). These systems were compared to current practice, i.e., large utility-scale power generation, electric chillers, and gas boilers. Both average U.S generation mix and high efficiency natural gas combined cycle (NGCC) power generation were investigated.

Three basic operational strategies were considered in this study: baseline, thermal load following, and electrical load following. Baseline cases refer to when U.S. average electric generation mix or NGCC were used to satisfy the electric load of the building, and the heating demand was satisfied by gas boilers. An alternative scenario substituted gas-fired absorption chillers for electric chillers.

In thermal load following cases (TLF), cogeneration systems were operated to meet the thermal energy use of the building, consisting of mainly space and water heating, as well as absorbtion cooling in summer months. The cogenerated electricity was used to meet part or all of the electric energy use of the building.

The cooling demand of the building in summer months (May and August) was satisfied by using absorption chillers (AC), driven by the heat produced from the cogeneration process. Supplemental electricity was imported from the grid when needed.

In electric load following cases (ELF), cogeneration systems were operated to meet the electrical energy use of the building, consisting of equipment, lighting and cooling. Cooling was by electric chillers (EC) in one scenario, and by a combination of absorption and electric chillers (AC/EC) in another. The cogenerated heat was used to meet part or all of the thermal energy use of the building. Supplemental heat was provided by gas boilers when required. In addition, in the AC/EC scenario, the cogeneration processes were operated to satisfy the cooling load.

Some of the assumptions made in the hourly scenarios were:

- There was no electric storage over the day and electricity from the grid (generated from average electric generation mix) was used when the co-generated electricity from the cogeneration processes did not meet the electric energy use of the building at different hours of the day in ELF scearios. Likewise, there was no thermal storage over the day and heat from gas boilers was used when the cogenerated heat from the cogeneration processes did not meet the thermal enery use of the building at different hours of the day in TLF scenarios. Thus, no credit was taken for electrical and thermal energy co-generated above the demand;
- No heat and electrical losses from cogeneration processes, other than those captured by the conversion efficiencies; and
- Load following can be applied.

Methodology

Energy simulation was used to obtain the electrical, heating, and cooling loads of the hypothetical building. The hypothetical office building had a floor area of 100,000 square feet. The location chosen for the building has less than 5500 heating degree days and less than 2000 cooling degree days. Data from the Commercial Building Energy Consumption Survey was used to determine the building's envelope characteristics and equipment loads (Sezgan, 1995).

Data from literature and previous studies is used in a life cycle assessment (LCA) framework. The environmental aspects and potential impacts are assessed throughout the product's life, i.e., cradle-to-grave. LCA software is used to develop and analyze the set of scenarios reviewed earlier.

The life cycle inventory includes unit processes with inputs, such as raw materials, fuels, auxiliary materials and energies, and outputs, such as, products, emissions, water and solid waste effluents, and electrical and thermal energies. These processes are linked to one another by the flow of products

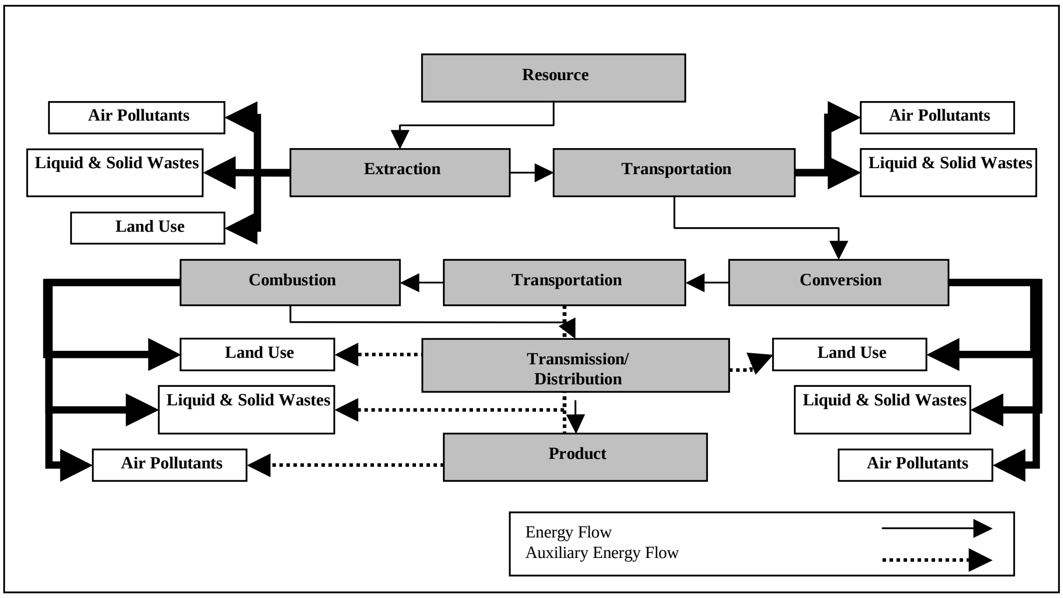

Figure 1 Energy Flow, Emission, Wastes, and Land Use Model

through transportation and distribution lines. Figure 1 shows a typical energy flow, emissions, waste, and land use model used in this study.

Primary energy consumption, global warming potential (GWP), tropospheric ozone precursor potential (TOPP), and acidification potential (AP) are the impact categories used to quantify the environmental impact from the energy systems' inventory.

DISCUSSION AND RESULTS ANALYSIS

Simulation Analysis

Figure 2 shows the hourly electric energy use of the building. The profiles represent three typical days in three months: January, May, and August. January represents a heating month. There is no cooling load and the electric load is mainly for equipment and lighting. May and August represent cooling months, where the electric load consists of cooling, equipment, and lighting. Two chiller types, electric and absorption, are considered in this study. Therefore, the cooling energy use is either added to the electric load or the thermal load depending on the scenario. When cooling is not included in the electric load, the electric energy use of the building is approximately equal for the three months and peaks during the working hours of the day (hours 8-17). The peak in electric load during summer months reflects the cooling energy demand. Figure 3 shows the hourly thermal energy use of the building. In Janaury, the thermal energy use consists mainly of space and water heating, which is higher during the non-working hours of the day and decreases during the working hours of the day. In May and August, the thermal energy required for heating is only for domestic water, which is relatively small. If cogeneration systems are used, there is the potential for reducing energy consumption by utilizing the cogenerated heat with absorption chillers. This is indicated in Figure 3 by the cooling energy profiles.

System Energy Production

Figures 4 and 5 show the electrical energy cogenerated from the cogeneration systems while following the thermal energy load of the building. Also, shown in the figures, (dashed line), is the electric energy use of the building. For TLF cases in January and May, the electric energy generated from the cogeneration systems follow the thermal demand profile shown in Figure 3.

The magnitude of the electric energy generated from the cogeneration systems in the TLF scenarios is proportional to their respective electric efficiency ratios. Cogeneration systems with high electric efficiency ratios produced more electricity than those with lower ratios. The SOFC produced more power than the 3-MW ICE followed by the 143-kW ICE and the microturbine. Their respective electrical efficiencies were 47%, 39%, 29%, and 28%.

In January, the results indicate that when the thermal load is high during non-working hours, cogeneration systems are able to meet the electric energy use of the building. As the thermal load decreases and the electrical energy use increases during working hours, the cogeneration systems are not able to meet the electrical demand during some hours, as shown in Figure 4. In these cases, if electric energy storage is not considered, then the cogeneration systems, especially those with low electric efficiency ratios, might not be an attractive alternative to conventional baseline systems, since supplemental electricity must be imported from the grid to meet the electrical demand. In May, the cogenerated electricity from the cogeneration systems in the TLF/AC scenario is

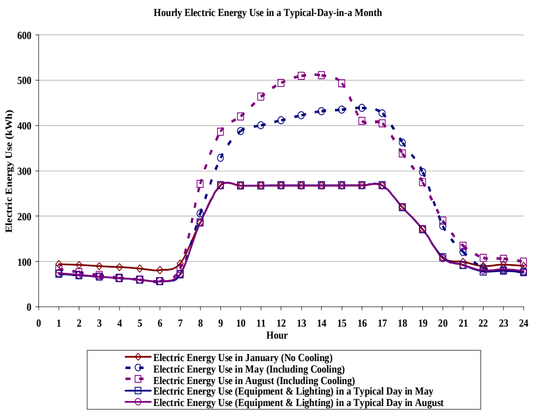

Figure 2. Hourly Electric Energy Use

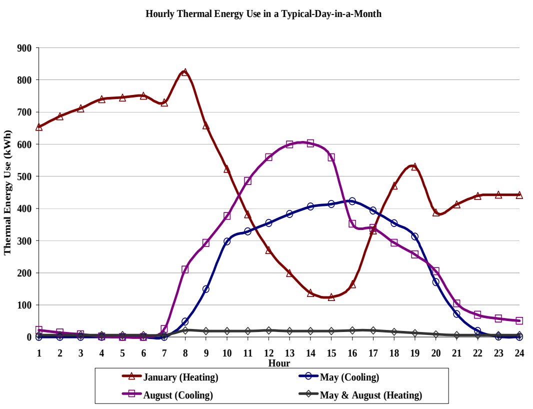

Figure 3. Hourly Thermal Energy Use

lower than the electrical energy load of the building without cooling, as shown in Figure 5, for all hours except for the working hours of the day when the thermal load peaks due to the increase in cooling demand. Even at those peak hours, only cogeneration systems with high electric efficiency ratios (SOFC and the 3MW ICE) are able to produce sufficient electricity to meet the building's demand. Thus, this particular operational strategy (TLF with AC for cooling) does not present an attractive alternative to conventional practice, since the non-cooling thermal load is relatively low in summer months.

Figures 6, 7, and 8, show the cogenerated thermal energy from the cogeneration systems while following the electrical use of the building (ELF). Also shown in the figures is the thermal energy use of the building required for heating and cooling when using an AC. For ELF cases in January and May, the profiles of the thermal energy generated from the cogeneration systems followed the electrical demand profile for January and May, refer to Figure 2. As shown in Figure 7, for May, when cogeneration systems are meeting the electric load of the building including cooling with an EC, the thermal energy profiles follow the electric energy use including cooling profiles (refer to Figure 2). On the other hand, as shown in Figure 8, when the cogeneration systems are meeting the electric load of the building consisting of equipment and lighting only, and cooling is met by an AC or combination of AC/EC, the generated thermal energy profiles from the cogeneration systems follow the electric energy use without cooling profiles shown in Figure 2. The magnitude of the thermal energy generated from the cogeneration systems is proportional to their respective thermal efficiency ratios. Cogeneration systems with high thermal efficiency ratios produce more heat than those with lower ratios. The microturbine produces more heat than the 143-kW ICE, followed by the 3-MW ICE, and finally the SOFC. Their respective thermal ratios were 52%, 51%, 41%, and 26%.

In January, because the electric load is low during non-working hours, the cogenerated heat is lower than the building's thermal demand, and hence supplemental heat is required during those hours. However, as the electric load increases during the working hours of the day and the thermal demand decreases, most cogeneration systems are able to meet the thermal demand during those hours except for systems with lower thermal efficiency ratios, such as the SOFC (see Figure 6). Therefore, if thermal storage is considered, cogeneration systems, especially those with high thermal efficiency ratios, would present the potential to reduce the thermal energy consumption by using their co-generated heat to meet the thermal demand.

In May, during all hours of the day, while following the electric load, all cogeneration processes using an EC produce more heat than the domestic heating requirement of the building. However, only cogeneration with high thermal efficiency ratios are able to meet the cooling requirement when using a combination of AC/EC during the working hours of the day, as shown in Figure 8. The microturbine and the 143-kW ICE using AC/EC are able to meet the cooling demand, whereas, the SOFC and the 3-MW ICE using AC/EC are not. In this scenario, the cogeneration systems with the AC/EC were used for supplementary cooling. Thus, from energy efficiency standpoint, in summer months with ELF cases, using a combination of AC/EC would be recommended for cogeneration systems with high thermal efficieny ratios.

LCA Analysis

As stated earlier, four environmental impact categories were used to quantify the potential

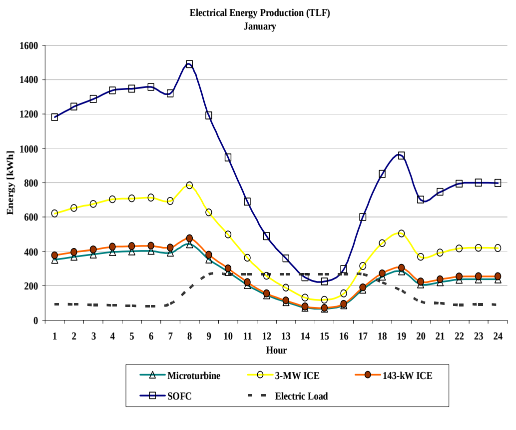

Figure 4. Electrical EnergyProduction in January (TLF)

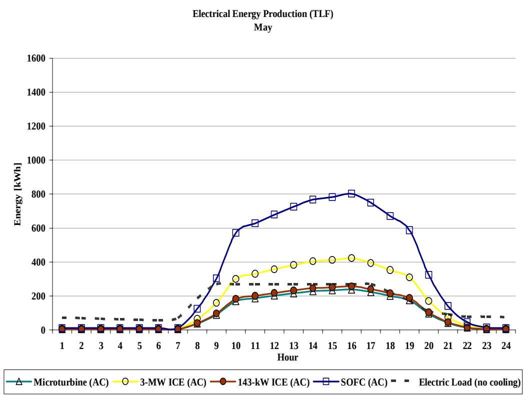

Figure 5 Electrical Energy Production in May (TLF)

contribution of the energy systems' inventory flow points. *Primary energy consumption* and *acidifcation potention (AP)* will be used as an illustration to demonstrate the relationship between the building load characteristics, operational strategies, and environmental impact.

Primary energy consumption represents a quantitative measure of the total amount of primary energy resources needed to deliver energy. The impact of primary energy use determines the availability of natural resources, which could be translated to issues, such as efficiency, conservation, and sustainable use.

Acidification potential (AP) is the result of aggregating acidifying air emissions, expressed in SO2 equivalents. Generally, the average electric generation mix (EC) has the highest unit AP while the SOFC (AC) has the lowest, and the NGCC (EC) has a unit AP similar to the cogeneraion processes.

Figures 9 and 10 show the primary energy consumption resulting from using the energy systems to meet the thermal and electrical energy use of the building using TLF for cogeneration systems. The primary energy consumption of the cogeneration processes correspond to their thermal efficiencies in TLF cases: processes with high thermal efficiencies consume less energy than those with lower ones. As shown in Figure 9 and Figure 10, primary energy consumption by all processes follow the thermal energy use profile (refer to Figure 3) of the building except when the cogeneration processes fail to meet the electric energy use of the building and require supplemental electricity from the grid.

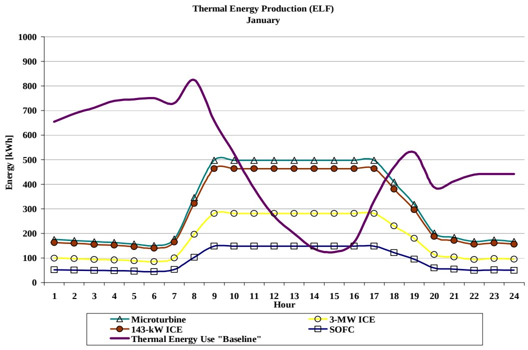

Figure 6 Thermal Energy Production in January (ELF)

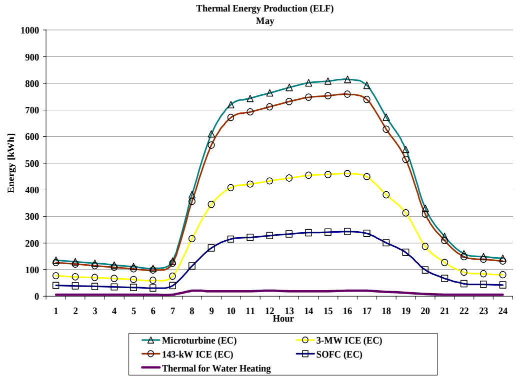

Figure 7. Thermal Energy Production in May (ELF)(EC)

As shown in Figure 9, during the non-working hours of the day in January, the NGCC followed by the average electric, (baseline cases), has the least primary energy consumption compared to the cogeneration systems, mainly because the electric energy use of the building is low at those hours and all the cogeneration processes cogenerate more electricity than required while following the thermal load of the building. However, as electrical energy use of the building increases during the working hours of the day, most cogeneration processes have lower primary energy consumption than the baseline cases, even though some of the cogeneration processes require supplemental electricity to meet the electric demand (refer to Figure 4).

In May, during non-working hours, all the cogeneration processes have primary energy consumption comparable to the average electric mix (EC) and the NGCC (EC) baseline cases (refer to Figure 10). This is because all of the cogeneration processes fail to meet the electric energy use of the building while following the thermal load (refer to Figure 5).

However, during the working hours of the day, as the cooling energy use of the building increases, the cogeneration processes are able to utilize some of the cogenerated electricity to meet the electric energy load of the building while following the thermal load. As shown in Figure 10, during these hours, all

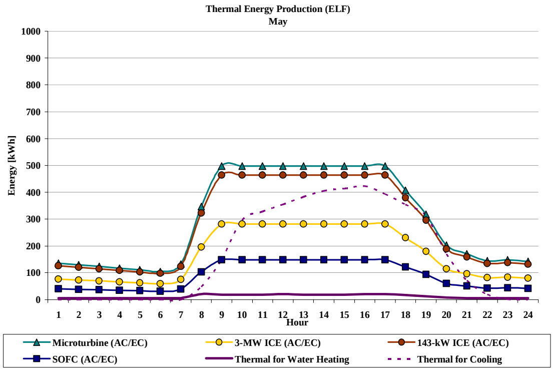

Figure 8 Thermal Energy Production in May (ELF) (AC/EC)

the cogeneration processes, except the SOFC (AC), have comparable primary energy consumption, which is lower than the average electric mix (EC) and the NGCC (EC). The SOFC (AC) has the highest energy consumption because it has a relatively low thermal efficiency ratio, and hence it doesn’t produce heat efficiently. It does produce a surplus of electrical energy in this scenario (refer to Figure 4).

As shown in Figures 11 and 12, AP emissions from the cogeneration processes follow the thermal energy use profile of the building (refer to Figure 2), except when processes fail to satisfy the electric energy use of the building and require some supplemental electricity.

Generally, although thermal efficiencies of the cogeneration processes are important factors when considering the primary energy consumption (and GWP) of the cogeneration processes, they are insignificant when considering AP (and TOPP).

The microturbine and the SOFC have significantly lower TOPP and AP than both the 3-MW ICE and the 143-kW ICE whether supplemental thermal energy is required to meet the thermal demand of the building or not.

Hence, in TLF cases, while the thermal efficiency ratio of a process is an important factor in predicting the primary energy consumption of a process, the electrical efficiency ratio of a process determines if a cogeneration process is a practical option because the resulting co-generated electricity from the process could be insufficient to meet the electrical load of the building and supplemental electricity might be required to meet the demand.

Figures 13, 14, and 15 show the primary energy consumption resulting from using the energy systems to meet the thermal and electrial energy use of the building (ELF for cogeneration systems). Figures 16, 17 and 18 show the AP of energy systems. The primary energy consumption of the

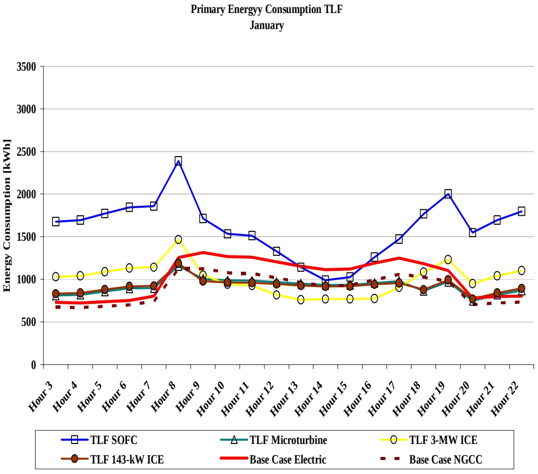

Figure 9 Primary Energy Consumption in January (TLF)

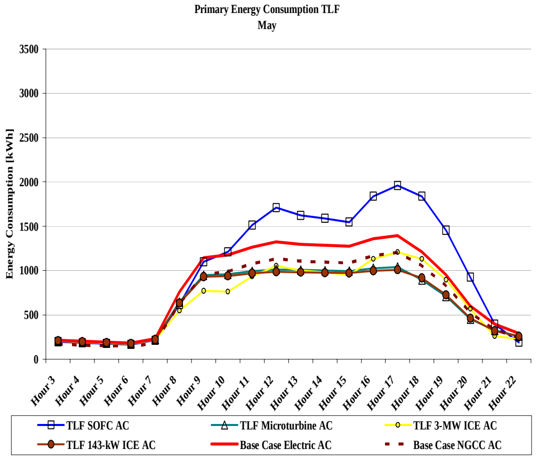

Figure 10 Primary Energy Consumption in May (TLF)

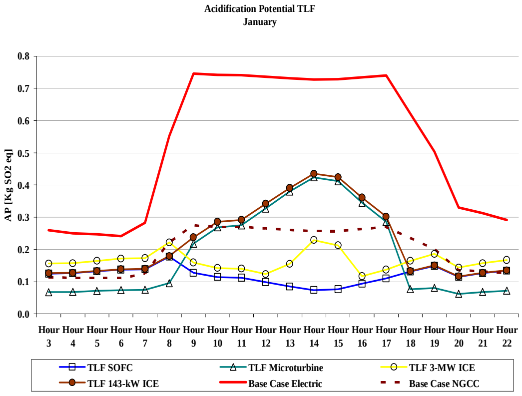

Figure 11 AP in January (TLF)

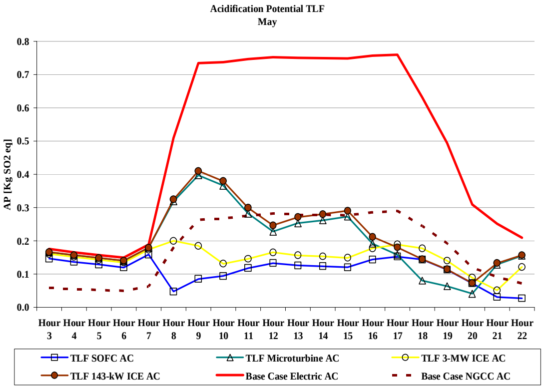

Figure 12 AP in May (TLF)

cogeneration processes correspond to their electrical efficiencies: processes with high electrical efficiencies consume less energy than those with lower ones. As shown in Figures 13, 14, and 15, primary energy consumption by all processes follow the electrical energy use profiles (refer to Figure 4) of the building except when the cogeneration processes fail to meet the thermal energy use of the building and require supplemental heat.

Figures 15 and 18 show that in May, when ELF cogeneration processes used a combination of absorption and electric chillers instead of electric

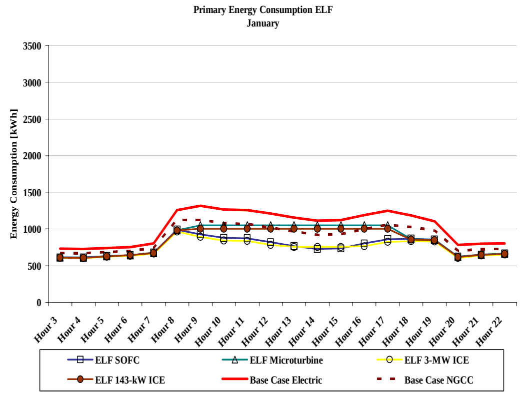

Figure 13 Primary Energy Consumption in January (ELF)

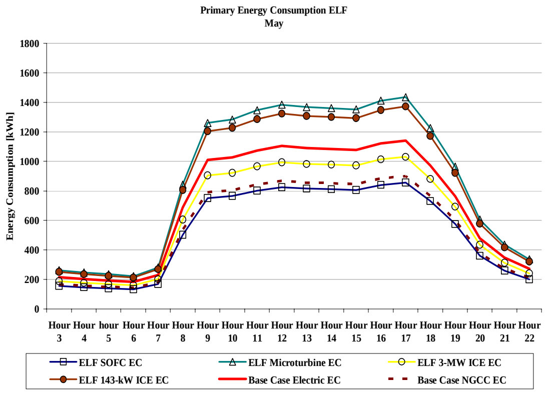

Figure 14 Primary Energy Consumption in May (ELF) (EC)

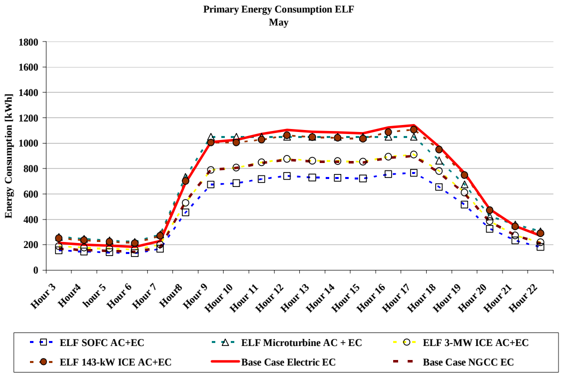

Figure 15 Primary Energy Consumption in May (ELF) (AC/EC)

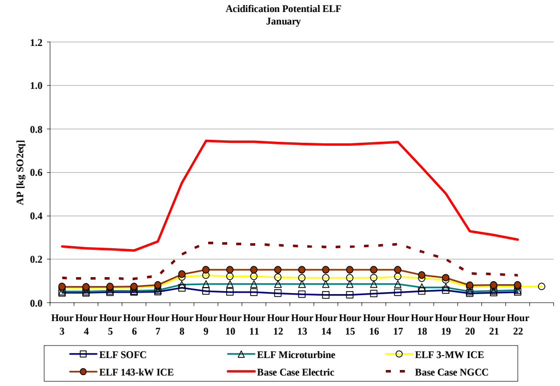

Figure 16 AP in January (ELF)

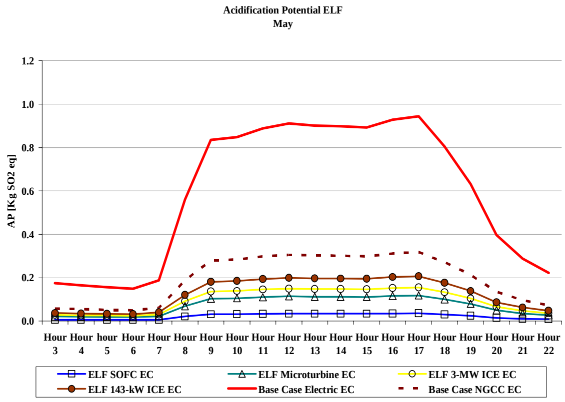

Figure 17 AP in May (ELF) (EC)

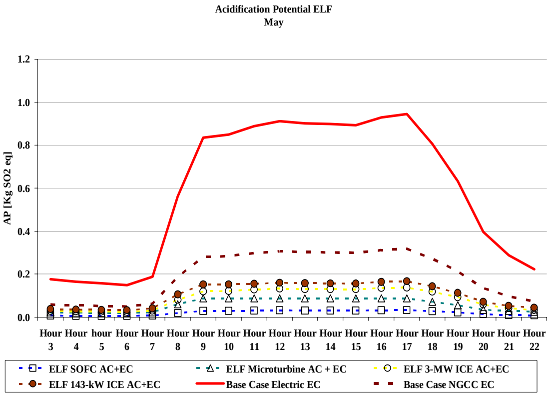

Figure 18 AP in May (ELF) (AC/EC)

chillers alone, shown in Figures 14 and 17, the energy consumption and AP are reduced significantly.

Generally, for electrical load following cases, while the electrical efficiency of a cogeneration system determined the amount of electricity generated and subsequently the amount of energy consumed, the thermal efficiency of the system affected the magnitude of the reduction in energy consumption and emissions.

When considering AP all cogeneration processes and the NGCC are better alternatives to the average electric generation mix, mainly because they use natural gas as the primary fuel, which has very low nitrogen and sulfur content compared to other fuels used in the average electric generation mix, such as coal.

CONCLUSION

From the analysis of the results, the performance of the cogeneration systems is generally affected by a) the building's load characteristics, and b) the thermal and electrical efficiency ratios of a cogeneration process. Using energy simulation for predicting the energy use of the building helps in identifying efficient approaches for the operation of cogeneration systems. Analyzing different operational strategies by obtaining the cogenerated electric and thermal energy following the thermal or electric load of the building and applying a life cycle assessment framework helps in understanding the systems' performance, quantify and allocate specific sources and causes of emissions, and, therefore, possibly identifying means to minimize the environmental impacts from such processes in the future.

Under the assumptions considered in this study, from the environmental impact perspective the electrical load following is found to be the optimal operational strategy for all cogeneration systems. The main findings are that cogeneration systems performed better with ELF when the thermal load of the building is high; energy consumption and emissions are reduced when AC or combination of AC and EC are used for cooling with cogeneration systems. SOFC using EC only (ELF) and the 3-MW ICE (ELF) using combination of AC and EC showed the best overall performance compared to the other systems.

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