Chapter 3

# CCHP System Performance Based on Economic Analysis, Energy Conservation, and Emission Analysis

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Additional information is available at the end of the chapter

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**Abstract**

This chapter includes the basic configuration of combined cooling heat and power (CCHP) systems and provides performance analysis based on energy, economic and environmental consideration applicable to buildings. The performance parameter for energy savings measure used for the analysis is primary energy consumption (PEC) of CCHP system. Parameters used for economic analysis are the simple payback period (SPP), annual savings (AS), internal rate of return (IRR) and equivalent uniform annual savings (EUAS). The emissions savings are determined for carbon dioxide (CDE), nitrogen oxides ($NO_X$), and methane ($CH_4$). Economic, energy, and emission performance criteria have been utilized for three types prime movers in five different building types, consisting of a primary school, a restaurant, a small hotel, an outpatient clinic, and a small office building. Performance for economic analysis indicated that economic savings career, unlike ICE, which is preferable in terms of economic and energy savings, emission analysis shows that micro-turbine poses be observed for the ICE in all building types, and the micro-turbine in some building types. For all types of prime mover based CCHP systems, lower $CO_2$ emission is observed for all building types. However, emission characteristics compared to other types of prime movers. Overall, CCHP system with optimum use of its appropriate prime movers can provide potential energy, economic and environmental benefit in buildings.

**Keywords:** CCHP systems, energy, ICE, micro-turbine, fuel cell, emission reduction, economic analysis

## 1. Introduction

Global energy demands are increasing on a daily basis and these demands are still being met with conventional methods of power generation such as burning coal and gasoline [1]. These resources are not only limited but also are detrimental to our environment [2]. Among different power consumers, buildings are major energy sink comprising 40% of total U.S. energy consumption [3]. Thus, the increasing demand for sustainable buildings with the constant need of cooling and heating power in buildings calls for improving traditional energy production and optimum use. One method to produce sustainable energy is to adopt the combined cooling, heating, and power (CCHP) technology, which is also known as trigeneration. Today, the CCHP system has proven effective in ensuring energy savings, as well as reducing the emission of pollutants [4]. This technology is a more advanced form of the combined heating and power (CHP) system and is becoming widely accepted with consumers. While a CHP system involves the simultaneous production of two types of energy such as electricity and heat, usually in the form of either hot water or steam, from one primary fuel, such as natural gas; the CCHP system, as the name implies, produces three forms of energy: electricity, heat, and chilled water [5]. Chilled water is achieved by incorporating an absorption chiller into a cogeneration system. Absorption chillers use the waste heat from a CCHP system to create chilled water to cool buildings. Introducing an absorption chiller into a CHP system allows a site (e.g., buildings) to increase its operational hours through the increased use of heat, which ultimately reduces energy costs [6]. Because of its abilities to save energy, reduce emissions, and provide economic benefits, the CCHP system has attracted much attention worldwide.

Burning fuels such as natural gas or coal results in significant amounts of heat energy and waste materials. Generally, a mechanical apparatus converts the heat energy into electrical energy [7]. However, a significant portion of heat energy is wasted and discharged into the environment [8], and such unused heat energy has significant potential that a CCHP system exploits. First, CCHP accomplishes cooling that is used to provide air conditioning, as the heat produced during electricity generation can be used to drive absorption chillers. Second, the CCHP makes maximum use of the waste heat from the prime movers to supply heat to the buildings and provide hot water for industrial processes. In this way, a CCHP system maximizes heat energy use in buildings and increases the prime mover efficiency. In the literature, it was reported that CCHP systems could yield efficiencies more than twice that of average power plant efficiency [9–11]. On the contrary, this percentage is not always constant. The electrical load may remain almost constant throughout the year and thus can maintain a certain level of fuel consumption. However, the demand for cooling and heating varies throughout the year. The demand for cooling is higher during summer and that for heating is higher during winter. However, during spring and fall, the need for both cooling and heating may decrease significantly, and in such cases, the efficiency of the CCHP system may decrease. However, this technology allows greater operational flexibility at sites (e.g., buildings) that demand energy in the form of heating as well as cooling [12]. That specific benefit is attractive in tropical countries where buildings need to be air-conditioned in all seasons as well as to industries that require process heating and cooling over the year. Finally, a CCHP system generates power in a way similar to that of conventional systems and can be utilized as a backup power system. This also reduces fuel and energy costs and $CO_2$ production compared to electricity produced from coal. All of these advantages have made the CCHP systems an economically viable alternative to produce power as well as to condition the building environment [13]. This chapter describes the history of CCHP, provides basic CCHP configuration, specifies types of prime movers, and provides performance parameters with basic economic analysis applicable to buildings. The results shown here include the use of CCHP in a cold, climate (Minneapolis, MN) for five different building types, consisting of a primary school, a restaurant, a small hotel, an outpatient clinic, and a small office building. The evaluation criteria to measure the performance parameters of the CCHP system are economic benefits, energy conservation, and emissions mitigation. Parameters indicating cost savings are the simple payback period (SPP), annual savings (AS), internal rate of return (IRR), and equivalent uniform annual savings (EUAS). The energy saving parameter used is primary energy consumption (PEC). The emission savings are determined for carbon dioxide (CDE), nitrogen oxides ($NO_X$), and methane ($CH_4$). Overall, the CCHP system has significant energy saving potential in both buildings and industries. It can also provide maximum sustainability in energy utilization in modern buildings.

## 2. History

Since the beginning of the electric age, power plants produced far more heat than electricity. In 1882, Thomas Edison used cogeneration of both steam and electricity in the world's first commercial power plant in New York [14]. Then, at the beginning of the twentieth century, steam became the principal source of mechanical power [15]. At the same time, energy became more controllable and many small power houses that produced steam to customers for space heating or industrial use realized that they might also produce electricity as well [16]. Because steam cannot be transported far without a significant loss of heat, cogeneration was dependent on a district energy strategy for small community plants. After World War II, there was significant growth in centralized power plants that could deliver electricity over a wide region [17]. During 1940–1970, the concept of a centralized electric utility that could deliver power to the surrounding area was developed, and as a result, steam no longer was a viable commodity. During that time, large utility companies became both reliable and comparatively inexpensive sources of electricity. That situation caused small power houses to stop using the CHP system and instead, they bought their electricity from the large utility companies. Further, as central utilities became more reliable and less costly, CHP remained economical only in industries that required large amounts of steam.

During the late 1960s and early 1970s, interest in CHP began to revive, and by the late 1970s, the need to conserve energy resources became clear [18]. During this time, legislation was passed in the United States to promote cogeneration because of its efficiency. Specifically, the Public Utilities Regulatory Policies Act (PURPA) of 1978 encouraged this technology by allowing CHP producers to connect to the utility network and to purchase as well as sell electricity. In times of shortfall, PURPA allowed CHP producers to buy electricity from utility companies at fair prices and also allowed them to sell their electricity based on the cost the utility would have paid to produce that power [19]. These conditions encouraged a rapid increase in CHP capacity in the United States. However, at that time, there was little government support for CHP in Europe because the cogeneration was not seen as a new technology and therefore was not covered under the European Community's energy program. However, some individual European countries, like Denmark and Italy, adopted separate energy policies that allowed them to incorporate CHP facilities in their future energy projects. At present, the EU generates 11% of its electricity using cogeneration [20]. Because of the price increment of energy types on the market and the need for heating and cooling energy in modern buildings, considerable research has been conducted to improve the CHP system [21]. The historical basis and success of CHP then led to further steps to expand the efficiencies of CHP to CCHP, as each new increase in energy recovered will result in higher efficiencies, lower fuel/energy costs, and fewer related emissions.

## 3. Basic CCHP system design configuration

Combined cooling, heating, and power (CCHP) systems consist of a decentralized power generation source where a portion of the heat released as a byproduct of generation eventually gets recovered rather than rejected to the atmosphere. There are four main units of a CCHP system: (a) power generation unit, which is referred to as the plant's prime mover, such as a gas turbine, (b) cooling unit, such as a single-effect absorption chiller, (c) a heating unit, such as the boiler, and (d) electrical generator as shown in **Figure 1**.

In the typical CCHP system, mechanical power is produced from a thermal generation unit, such as a gas turbine. The mechanical power produced gets utilized to rotate an electrical generator. The generation unit produces waste heat, including exhaust gases and lubrication oil that is recovered to meet the cooling and heating demands of the building or industrial unit. One portion of waste heat is used to meet the heating demand, such as a building's heating load, while the remaining portion is used to meet the cooling demand. Moreover, cooled water from the chiller is used as a working fluid for the heat supply from the condenser and absorber of the chilling machine. CCHP systems provide cooling by using low quality heat (low temperature

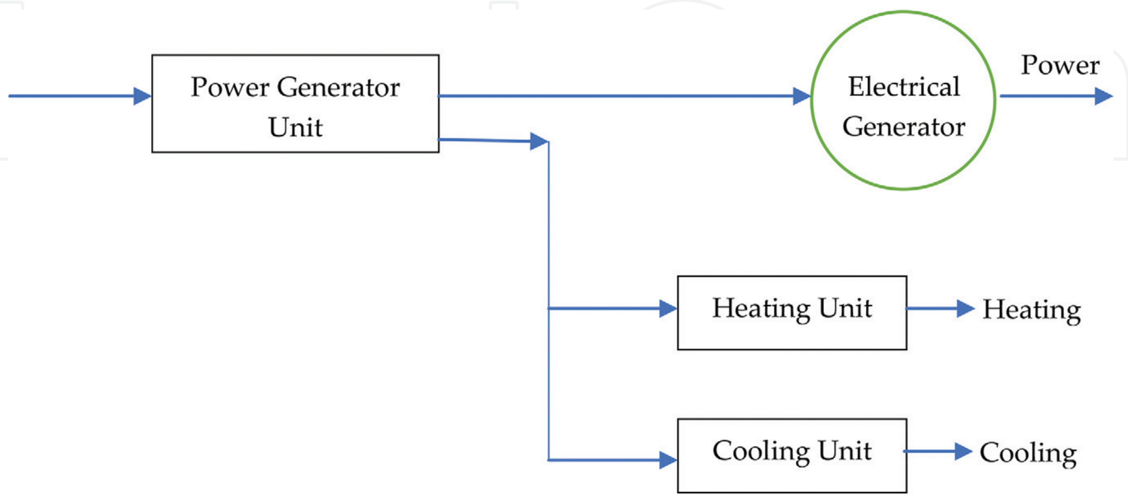


**Figure 1.** Schematic of a typical CCHP system.

and low pressure) discharged from the prime mover to drive the adsorption chillers and thus reduce the primary energy consumption overall.

## 4. Prime movers

The adoption of the CCHP system in buildings is mainly dictated by the main component of the CCHP system, its prime mover. Other components of the CCHP system (e.g., heating unit and cooling unit) do not have significant effects on its adoption in buildings. Several types of prime movers have been utilized for CCHP systems, including internal and external combustion engines, steam, gas, and microturbines, and fuel cells [22]. These different types of prime mover distinguish one CCHP from another. The number of prime movers varies depending on the electricity load demand. Operating with more than one fuel type adds flexibility to the prime mover's operation. However, the fuel type affects the greenhouse gas emission rate. For example, natural gas combustion produces fewer greenhouse gas emissions than do diesel combustion.

An internal combustion engine (ICE) system (**Figure 2a**) is the most common type of a prime mover. The merit of ICE systems depends on how often CCHP generation is required [23]. In this system, heat can be recovered from exhaust gases and the engine's cooling circuit. Moreover, heat is generated from exhaust gases for the absorption chilling machine. Cold water limits the operating temperature of the engine and uses thermal energy from exhaust gases in

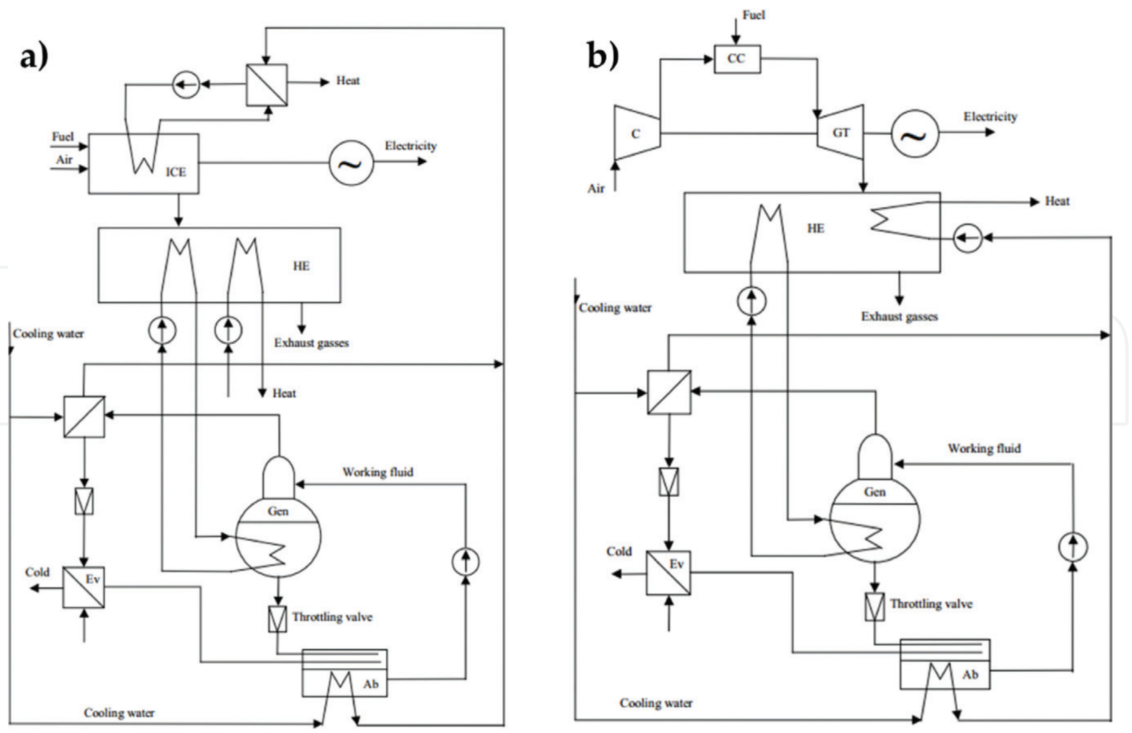


**Figure 2.** Simplified scheme of a trigeneration plant with (a) internal combustion engine with absorption chilling machine and (b) gas turbine with absorption chilling machine [23].

the heat exchanger to generate hot water or steam. In most cases, it is used to produce cooling energy by electric refrigerators. On the other hand, when the prime mover is a gas turbine (**Figure 2b**), the turbine generates electricity. In this case, heat generated from exhaust gases can be delivered to the users and a portion of it is used as a driving force for the absorption chilling machine. The other mechanisms are similar to those in the ICE system.

The prime mover of a steam turbine CCHP system is a steam boiler that needs fuel and air input to produce high pressure steam that feeds the steam turbine. When steam expands in the steam turbine, a portion of the thermal steam energy is transformed into mechanical energy. Moreover, the rotor of the electric generator is connected to the same turbine shaft, so ultimately, the mechanical energy is transformed into electricity.

The CCHP system design with microturbines is slightly older and dates back to the twentieth century [21]. Microturbines are small electricity generators that burn gaseous and liquid fuels to create high-speed rotation that turns an electrical generator. These are ideal prime movers for decentralized CCHP systems with small-scale rated power (**Figure 3**). This system has attracted attention because it has several benefits over other prime movers. The size range for microturbine available and in development is from 30 to 400 kilowatts (kW), while conventional gas turbine sizes range from 500 kW to 350 megawatts (MW) [24]. Moreover, microturbines run at high speeds and, like larger gas turbines, are able to operate on a variety of fuels, including natural gas, sour gases (high sulfur and low Btu content), and liquid fuels, such as gasoline, kerosene, and diesel fuel/distillate heating oil [25]. In resource recovery applications, they burn waste gases that otherwise would be flared or released directly into the atmosphere.

The CCHP system that uses the Stirling engine (**Figure 4**) as a prime mover can be used as energy sources for small commercial and residential buildings. It can operate with a wide variety of fuels, including all fossil fuels, biomass, solar, geothermal, and nuclear energy [26]. The external combustion that controls the combustion process results in low emissions, noise, and waste heat flow [27]. Another major advantage of the Stirling engine is that it can work at low temperatures [28].

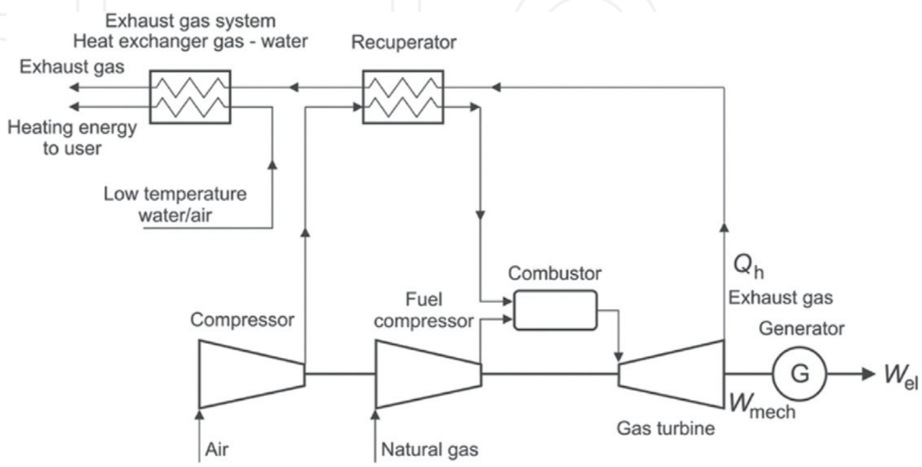


**Figure 3.** CCHP system design with a microturbine as a basic aggregate [21].

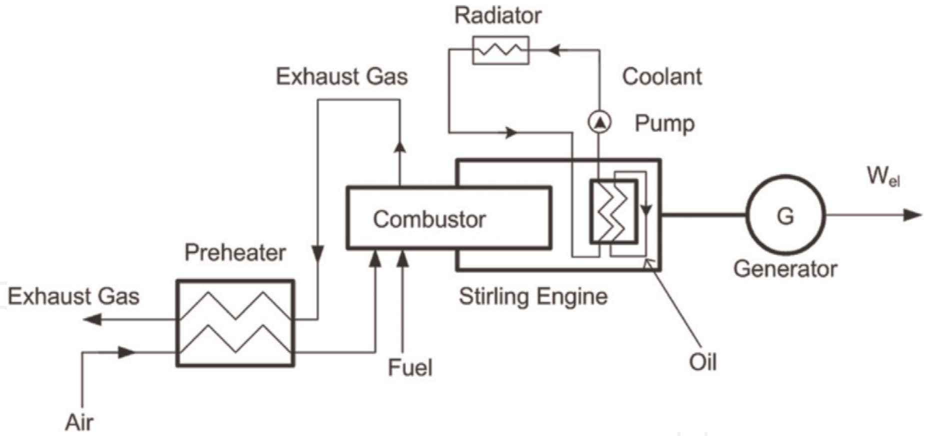


**Figure 4.** CCHP system design with the Stirling engine as a basic aggregate [21].

CCHP systems with a fuel cell as a prime mover are promising because of their potential to generate electricity and thermal energy directly. In this system, membrane steam reformers purify hydrogen without cooling the reactor's effluent. Before electrooxidation at the fuel cell's anode, only permeated hydrogen needs to be cooled. Both the absorption and compression heat pumps use the fuel cell's waste heat and electricity for heating and cooling applications [29]. Moreover, high-temperature fuel cells combined with an absorption chiller offer the potential to meet the criterion of virtually zero pollutant emissions [30].

## 5. Performance parameters of CCHP

In order to determine the best performance parameters and boost the performance for the CCHP system, several equations have been applied. Equations to determine the GHG emissions [e.g., carbon dioxide (*CDE*), nitrogen oxides (*NXE*), and methane (*ME*)] have been set as well. Moreover, methods to calculate the annual cost savings and primary energy consumption (*PEC*) can also be represented with appropriate equations and are presented in [31]. All of these equations to calculate the performance parameters are presented in this section. The annual cost savings have been reported as dollar amount and the *CDE*, *NXE*, *ME,* and *PEC* were reported in terms of "relative savings" with respect to the reference quantities.

### 5.1. Economic analysis

Eq. (1) can be used to calculate the total annual operating cost (*AOC*) of the CCHP system together with the reference system. Parameters $C_{NG}$ and $C_{elec}$ used in Eqs. (1) and (2) are the cost of natural gas and electricity, respectively. The operational (excluding fuel) and maintenance cost per unit of energy produced by the *PM* is designated as *COM*. The value represents the energy produced during the *i*th interval. The annual savings can be calculated by deducting $AOC_{PM}$ from the $AOC_{ref}$ as shown in Eq. (3).

$$AOC_{PM} = \sum_{i=1}^{8760} F_{mi} C_{NG} + E_{grid_i} C_{elec} + P_{PM_i} C_{om} \tag{1}$$

$$AOC_{ref} = \sum_{i=1}^{8760} F_{mref_i} C_{NG} + E_{grid_{ref_i}} C_{elec} \tag{2}$$

$$AS = AOC_{ref} - AOC_{PM} \tag{3}$$

As shown in Eq. (4), the calculation of the simple payback period (*SPP*) depends on the *AS* calculation [32].

$$SPP = \frac{IC}{AS} \tag{4}$$

where, *IC* is the initial cost. A discounted cash flow method, such as internal rate of return (*IRR*), is also used to evaluate these CCHP systems. CCHP is attractive for building operations when *IRR* is greater than the minimum attractive rate of return (*MARR*). *IRR* can be calculated from the Eq. (5).

$$IC = \mathrm{AS}\left[\frac{(1+IRR)^{L_{PM}} - 1}{IRR(1+IRR)^{L_{PM}}}\right] \tag{5}$$

where, *LPM* is the lifetime of the *PM* [29]. Another discounted cash flow method is the net present value (*NPV*) for CCHP systems. *NPV* can be calculated as shown in Eq. (6):

$$NPV = \sum_{n=0}^{N} \frac{AS}{(1+i)^n} - IC \tag{6}$$

where, $i$ is the discount rate, $n$ is the time of cash flow (period), and $N$ is the total number of periods. A third analysis that uses discounted cash flow is the equivalent uniform annual savings. First, the equivalent uniform annual cost is determined according to

$$EUAC = IC\frac{\xi(1+\xi)^{L_{PM}}}{(1+\xi)^{L_{PM}} - 1} \tag{7}$$

where, $\xi$ is the interest rate, chosen as a representative value for bank offered rates. Equivalent uniform annual saving can then be calculated from

$$EUAS = EUAC - AS \tag{8}$$

### 5.2. Energy consumption

Savings in primary energy consumption can be calculated by

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$$PEC_s = \sum_{i=1}^{8760} \frac{\left(F_{mref_i} PF_{NG} + E_{grid_{ref_i}} PF_{elec}\right) - \left(F_{mi} PF_{NG} + E_{grid_i} PF_{elec}\right)}{F_{mref_i} PF_{NG} + E_{grid_{ref_i}} PF_{elec}} \tag{9}$$

where $PF_{elec}$ and $PF_{NG}$ are the primary energy conversion factors for electricity and natural gas, respectively. Values for this study are given in **Table 1**.

### 5.3. Emission characteristics

The equations for the reduction in emissions for all three gases considered in this study, relative to the reference system, are represented by [33]:

$$Em_{s,g} = \sum_{i=1}^{8760} \frac{Em_{ref_i} - Em_{CCHP_i}}{Em_{ref_i}} \tag{10}$$

Here, $g$ in the subscripts represents the gas for which the savings are being calculated, i.e., represents the emission savings for carbon dioxide ($g$ = $CD$), nitrogen oxides ($g$ = $NX$), and methane ($g$ = $M$) are the emissions from the reference case and are the emissions obtained when the CCHP system is operated and can be calculated by

$$Em_{CCHP} = F_m EF_{NG,g} + E_{grid} EF_{elec,g} \tag{11}$$

$$Em_{ref} = F_{mref} EF_{NG,g} + E_{grid_{ref}} EF_{elec,g} \tag{12}$$

where, $EF_{NG,g}$ and $EF_{elec,g}$ are the emission factors for the respective gases from natural gas and electric sources as shown in **Table 1**. Emission conversion factors tabulated in **Table 1** can be used to determine the overall emissions of $CO_2$, NOx, and $CH_4$. The installation location of the PM in the CCHP system and fuel types required for electricity influence the emission

| Variable | Symbol | Value | Unit |
|---|---|---|---|
| Electric cost | $C_{elec}$ | 0.0757 | \$/kWh |
| Natural gas cost | $C_{NG}$ | 0.0125 | \$/kWh |
| Electric $CO_2$ emission | $EF_{elec,CD}$ | 0.682 | kg/kWh |
| Natural gas $CO_2$ emission | $EF_{NG,CD}$ | 0.181 | kg/kWh |
| Electric $NO_x$ emission | $EF_{elec,NX}$ | $1.12 \times 10^{-5}$ | kg/kWh |
| Natural gas $NO_x$ emission | $EF_{NG,NX}$ | $8.54 \times 10^{-7}$ | kg/kWh |
| Electric $CH_4$ emission | $EF_{elec,M}$ | $8.26 \times 10^{-6}$ | kg/kWh |
| Natural gas $CH_4$ emission | $EF_{NG,M}$ | $1.17 \times 10^{-8}$ | kg/kWh |
| Electric PEC factor | $PF_{elec}$ | 3.5 | — |
| Natural gas PEC factor | $PF_{NG}$ | 1.09 | — |

**Table 1.** Cost of fuel and electricity, gas emissions as well as PEC factors for Minneapolis, MN [32].

conversion factors. Emission is also observed in the reference system because of the grid electricity generation produced originally in the power plant. Emissions of the reference system are also due to the local boiler. Three factors dominate the emissions caused by CCHP: (i) electricity produced by the CCHP systems, (ii) electricity generation process of the power plant, and (iii) heat produced by the boiler.

## 6. Economic analysis

The CCHP system has drawn great interest because of its potential in prolonged economic benefit with short payback on initial capital investment. However, economic benefit is not a straightforward evaluation, which depends on the equipment cost, equipment efficiency, electricity and fuel cost, building electric demand, heating and cooling load, etc. These factors depends on the local climate condition, equipment variability, budget restriction, energy saving credits, and capital incentives to use any particular type of prime mover (PM) systems. Among those, the most significant ones that affects the economics of CCHP systems are the types of PM and weather zone effect on building load. Selecting a new PM for CCHP over a reference system is not always by simple payback period analysis, the building owners or investor may inclined toward a particular PM due to any favorable capital incentives offered

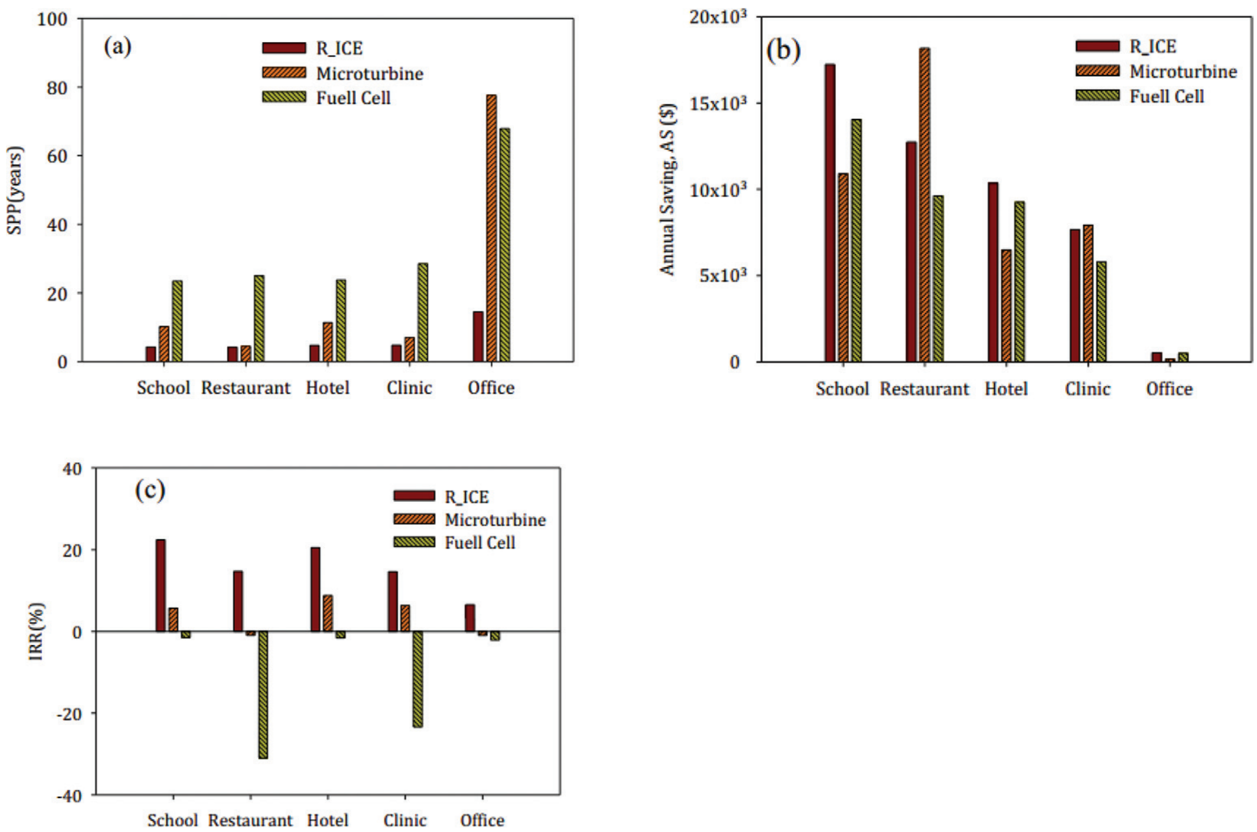


**Figure 5.** (a) *SPP*, (b) *AS*, and (c) *IRR* comparison of CCHP installed building types with the reference building [32].

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by government entities. The economic benefits of the CCHP system can also be significantly affected by local climate conditions since it changes the building heating and cooling demand.

Generally, the parameters used to determine economic benefits are the simple payback period (*SPP*), annual savings (*AS*), internal rate of return (*IRR*), and equivalent uniform annual savings (*EUAS*). Previous research has shown that the CCHP system is able to satisfy the energy demands of a building when it is integrated with the electric grid to achieve positive values of EUAS, IRR, and *AS* [32]. **Figure 5** shows the economic benefits for the three different prime movers in a case study conducted in Minneapolis, MN. The reciprocating internal combustion engine (*ICE*) demonstrated the greatest economic benefits overall across all building types. It also resulted in the best *IRR* values among the three prime movers. Moreover, the reciprocating *ICE* provided the maximum savings based on the *EUAS* values calculated. Based on the study, a fuel cell was the least economically advantageous and resulted in negative *EUAS* values for all building types. The reason for the net loss is attributable to the high capital cost of the fuel cell. However, the selection of a new prime mover for the CCHP generally depends on the analysis of economic parameters, as well as project details. Further, budget restrictions, credits for energy saving, and capital incentives need to be considered when selecting the prime mover.

## 7. Energy conservation

The CCHP system is an effective way to save energy over customary system with separate cooling and heating systems as it uses prime mover exhaust to heat and cool the building. This provides an alternative for the world to meet and solve energy-related problems, such as energy shortages and supply security, emission control, etc. Comprehensive analysis is often warranted to decide on appropriate prime mover for a CCHP system, which relies on the tradeoffs between energy savings, environmental impacts, and economics benefit. CCHP system's energy performance is greatly depends on the site weather zone, it works with maximum efficiency where heating, cooling, and electricity demands are mostly uniform through most or all of the year. However, energy savings will be significantly high if the installation site has higher heating demand, as it is more efficient to utilize the low quality thermal energy from PM exhaust to heat the facility rather use that energy to cool the building.

Generally, the energy conservation parameter for the study is the primary energy consumption (*PEC*) [32]. Another parameter, referred to as site energy consumption (*SEC*) always increases when the CCHP is used [33]. In contrast, the PEC is a better indicator of energy feasibility because of its potential to decrease when the CCHP is operational [33]. **Figure 6** shows the PEC results of the energy analysis in the case study conducted in Minneapolis, MN, where the reciprocating ICE and fuel cell showed almost similar energy (PEC) savings. All types of buildings experienced reductions in PECs when a CCHP system was adopted. When only the primary energy savings are considered in the absence of an economic analysis, all three prime movers are good options for the three building types.

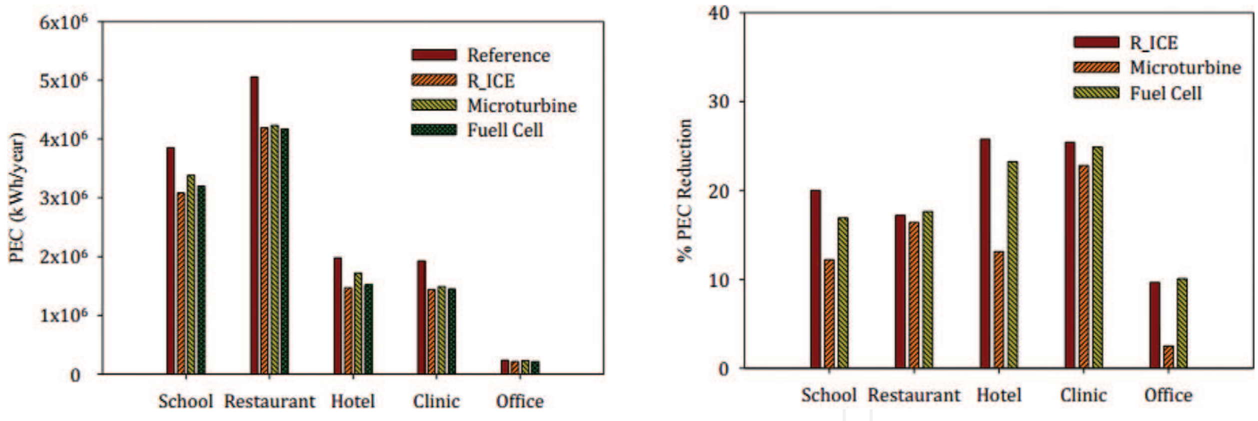


**Figure 6.** PEC comparison of CCHP installed building types with the reference building in Minneapolis, MN [32].

## 8. Emission analysis

Emission savings could be a significant decisive factor to implement the CCHP system over traditional heating and cooling system separately. Government agencies or ecofriendly industries are always inclined toward installing energy systems (i.e., CCHP) with better emission characteristics even with non-attractive economic benefit. In recent years, various federal, state or local government agencies offered carbon credit as an emission incentive to promote energy efficient technology like CCHP systems to industries and residential consumers. The CCHP system could be economically feasible with carbon credit even when SPP, IRR, and EUAS show negative economic return for the CCHP system over a traditional building air conditioning unit.

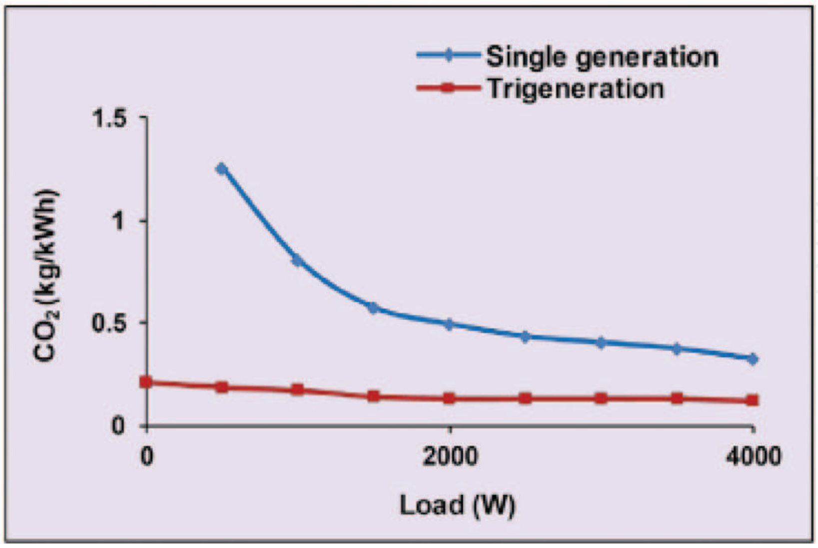


**Figure 7.** Sample of variation of carbon dioxide with load [34].

CCHP reduces $CO_2$ emissions significantly across a varying range of loads typical of micro-scale systems. **Figure 7** shows that $CO_2$ emissions per unit (kWh) of useful energy output results in a 61% reduction of $CO_2$ when a trigeneration system operates at full load compared to a single generation system [34].

A case study conducted a detailed emission analysis for a CCHP system to compare it to emissions of a reference system, which is presented in [30]. **Figures 8–10** summarize

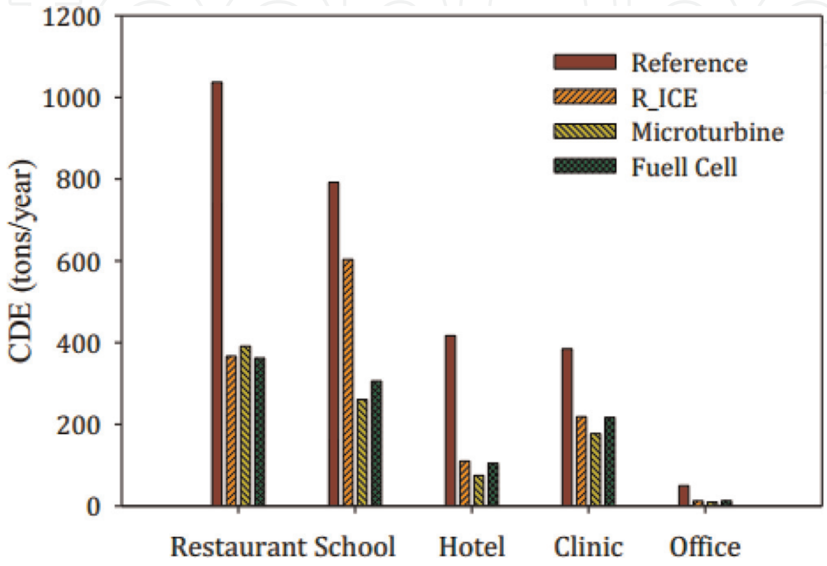


**Figure 8.** $CO_2$ emissions of reference building compared with CCHP installed different building types in Minneapolis, MN [32].

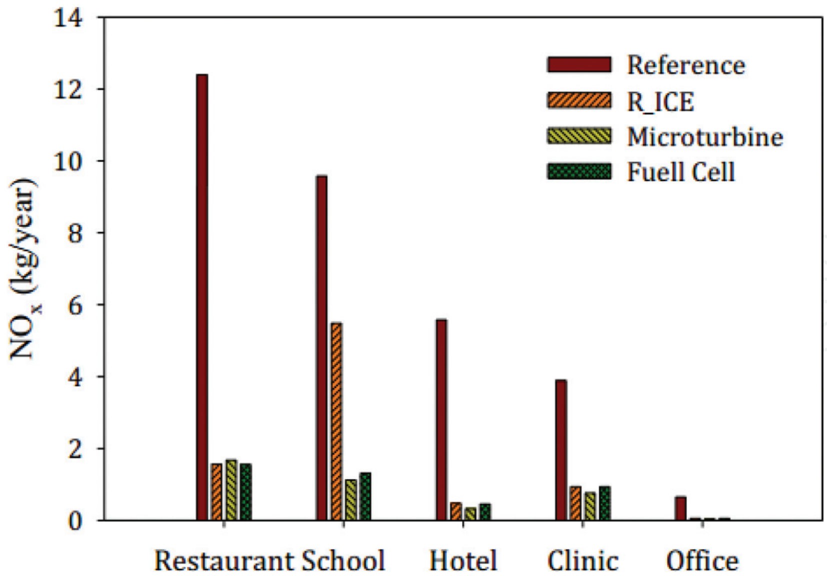


**Figure 9.** NOx emissions of reference building compared with CCHP installed different building types in Minneapolis, MN [32].

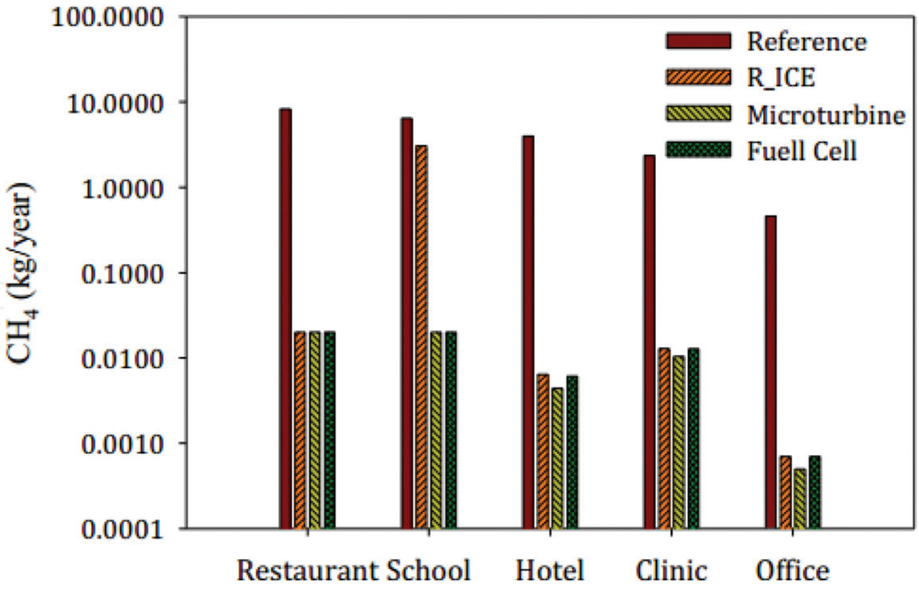


**Figure 10.** $CH_4$ emission of reference office building compared with CCHP installed building in Minneapolis, MN [32].

those emission results for the three gases analyzed. All three prime movers reduced emissions significantly and the microturbine provided the greatest reduction. For different building types, carbon dioxide emission savings show the highest savings occurred for the small hotel and small office. The reduction in carbon dioxide in the small hotel from the reciprocating ICE, microturbine, and fuel cell were 73.7, 82.0, and 74.9%, respectively. Overall, all building types experienced a reduction in emission from the implementation of CCHP systems. All three prime movers provided significant reduction in emissions; however the microturbine provided the most.

## 9. Summary

Buildings are major energy sink comprising 40% of total U.S. energy consumption. Energy savings in buildings often do not come with economic and/or environmental benefit. Additionally, the optimum use of energy and prevention of energy loss in buildings can entail additional challenges. This chapter on CCHP shows significant promise of CCHP being adopted in buildings widely not only because of its superior capacity for optimum energy use/savings but also for its additional economic and environmental benefit. It is evident that the evolution of the CHP system to CCHP system makes it more beneficial for its wide scale use in buildings. Appropriate performance parameters relevant for buildings' energy, economic and environmental benefit were determined and applied to assess the different prime movers use in CCHP for buildings. A CCHP system either with ICE or microturbine prime mover shows significant benefit in terms of energy, economic and environmental consideration for buildings. Thus, CCHP has significant role to play for overall energy independence of buildings in twenty-first century.

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