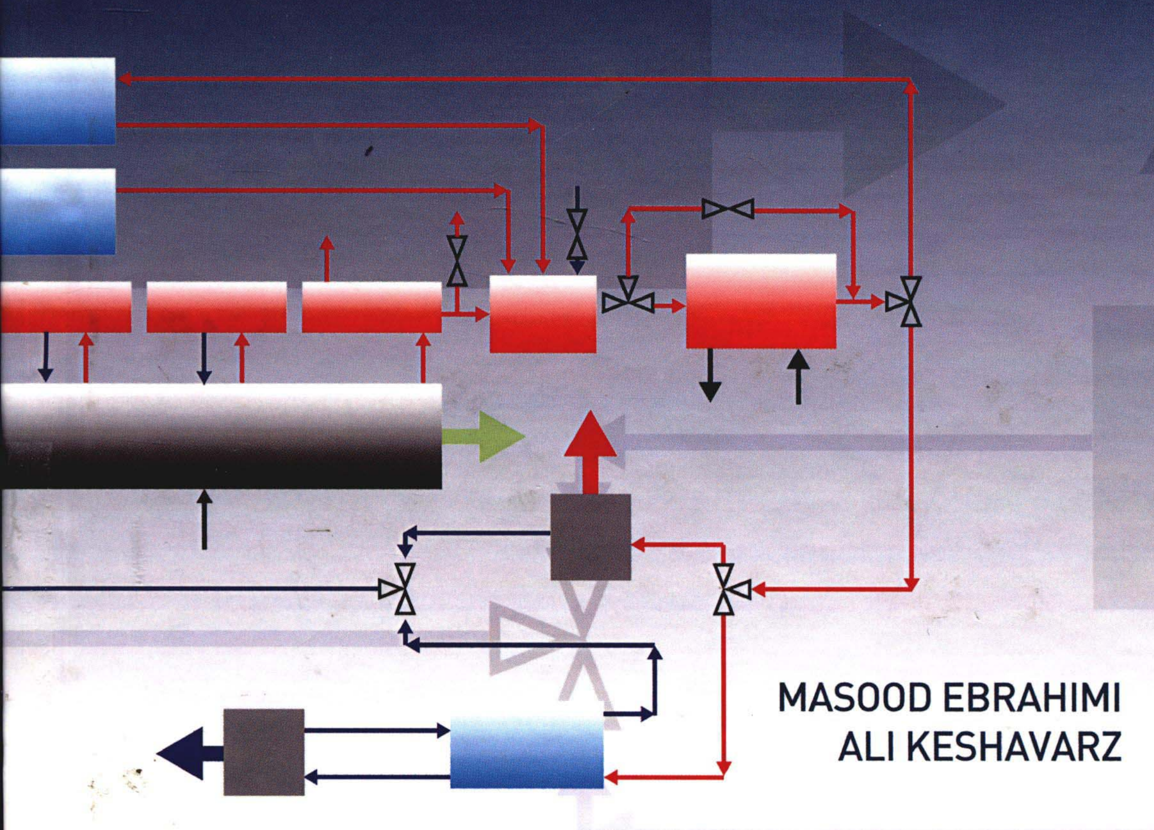
ELSEVIER

COMBINED COOLING, HEATING AND POWER

DECISION-MAKING, DESIGN AND OPTIMIZATION



MASOOD EBRAHIMI
ALI KESHAVARZ

Combined Cooling, Heating and Power

Decision-Making, Design and Optimization

Masood Ebrahimi
Assistant Professor at University of Kurdistan, Iran

Ali Keshavarz
Associate Professor at K.N. Toosi University of Technology, Iran

ELSEVIER

AMSTERDAM • BOSTON • HEIDELBERG • LONDON • NEW YORK
OXFORD • PARIS • SAN DIEGO • SAN FRANCISCO • SINGAPORE
SYDNEY • TOKYO

Elsevier
Radarweg 29, PO Box 211, 1000 AE Amsterdam, Netherlands
The Boulevard, Langford Lane, Kidlington, Oxford OX5 1GB, UK
225 Wyman Street, Waltham, MA 02451, USA

British Library Cataloguing in Publication Data
A catalogue record for this book is available from the British Library

Library of Congress Cataloging-in-Publication Data
A catalog record for this book is available from the Library of Congress

ISBN: 978-0-08-099985-2

For information on all Elsevier publications
visit our website at http://store.elsevier.com/

Printed in the United States of America

Combined Cooling, Heating and Power

Dedication

There is no shortcut to writing a book.
It needs the absolute support of family.
To my wife and my little son

Masood Ebrahimi

To my family
By whom I was encouraged
To my students
By whom I was inspired

Ali Keshavarz

Preface

Investigation of combined cooling, heating, and power (CCHP) systems by different researchers in the last decade have revealed that CCHP is reliable and economical. It saves fuel and reduces air pollution and greenhouse gases. It is also safer with respect to centralized power generation systems in critical situations such as war, terrorist attacks, and natural disasters. Due to these essential characteristics it is predicted that the use of distributed power generation such as CHP and CCHP systems will develop rapidly in the near future.

This book is written as a guide for CCHP researchers, designers and operators. The contents of this book can accelerate the new research and save considerable time for those who are new to this topic. This book also presents some general guidelines for operation and maintenance of CCHP systems.

In Chapter 1 most of the published research from 2002 to 2013 is summarized. The main attention of this literature review is to present the main design and decision-making criteria that concern researchers and designers. In addition different CCHP cycles presented by different investigations are discussed and presented. Through this literature review, the reader will become familiar with many CCHP cycles and their components.

In Chapter 2 the main technologies used in the basic CCHP cycles are introduced. These technologies include different prime mover types such as steam turbines, gas turbines, reciprocating internal combustion engines, micro-gas turbines, micro-steam turbines, Stirling engines, fuel cells and thermal photovoltaic technology. The basic CCHP cycles that can be designed with different prime movers are also presented. Furthermore, cooling system technologies, especially those that are thermally operated, are presented in this chapter. Thermally activated cooling systems include absorption chillers, adsorption chillers, solid and liquid desiccant dehumidifiers, and ejector refrigeration systems.

In the third chapter the main recommended evaluation criteria for use in the decision-making and design steps are introduced and formulated. The criteria are classified into four main groups: technological, economical, environmental, and miscellaneous. Every criterion is also divided into several subcriteria. For example, the technological subcriteria include fuel saving, exergy efficiency, overall efficiency, operation in partial load, maturity of the technology, recoverable heat quality, user-friendliness of control and regulation, etc. The economical subcriteria include initial capital cost, operation and maintenance cost, net present value, payback period, internal rate of return, net cash flow, etc. The environmental subcriteria may include reduction of air pollution such as CO_2, CO, and NO_x as well as noise. The miscellaneous subcriteria may include many parameters such as the footprint, ease of maintenance, import and export limitations on CCHP components, lifetime, etc.

In the fourth chapter, two methods are presented for decision-making for certain CCHP components, such as the prime mover, cooling, or heating systems. Decisions are made based on the fuzzy logic, and the grey incidence approach. These methods are called multicriteria decision-making methods. In this chapter, as an example, the prime mover of a CCHP system is chosen among several options for various climates.

To design a CCHP system, load calculation is one of the most important steps. In Chapter 5 different load calculation methods that can be used to design a CCHP system are presented. In addition, the load calculators and websites that can be used for finding necessary weather information are introduced. Also in this chapter the energy demands of a sample building in five different climates are calculated and compared.

In Chapter 6 different design methods for CCHP systems are presented. These methods include the classic maximum rectangle method (MRM); developed MRM; energy management sizing methods including FEL, FTL, and FSL; the thermodynamical sizing method; the thermoeconomical sizing method; the multicriteria sizing function; and the fitness function method. In addition a CCHP system is designed for five sample climates by using different sizing methods and the results and advantages and disadvantages of sizing methods are compared as well. This chapter is especially helpful for designers.

Using renewable energy sources besides fossil fuels in CCHP systems increases the capabilities of this new technology. In the seventh chapter solar heat in particular is studied for use in CCHP systems. A solar collector is coupled with the CCHP cycle and a method is proposed to determine the optimum direction and size of the collector in five climates.

Since usually the surplus heat is wasted in heating systems and basic CCHP cycles in particular, storing the surplus heat for reuse at a later time can increase the advantages of the CCHP system. In Chapter 8 the principals of thermal energy storage (TES) systems are introduced and the CCHP cycle designed in the previous chapters is equipped with the TES system.

Operation and maintenance of CCHP systems is a great job. A proper operation and maintenance program maintains the CCHP cycle in optimum condition, increases its life span and reliability, and decreases maintenance costs. In Chapter 9 the basics of operation and maintenance, pre-commissioning, commissioning, post-commissioning, and troubleshooting of CCHP cycles are presented as a guideline for operators.

Finally in Chapter 10 the mutual benefits of CCHP cycles for consumers and the government are discussed; this positive impact highlights a bright future for CCHP systems.

We believe that CCHP systems can be reliable as an energy conversion equipment because they use fuel energy very efficiently in comparison with the conventional systems for producing cooling, heating, and power. They are also helpful in reducing the risk of global warming. They are safer in critical situations such as war, terrorist attack, and natural disasters such as flood, earthquake, and thunderstorms.

We believe that this book is just an introduction for the decision-making process for CCHP systems and the design, and optimization of them. We appreciate every proposal, correction, question, comment, or criticism on this book with our heart and soul. The readers can write letters about the book to Dr. Masood Ebrahimi, University Of Kurdistan, Kurdistan Province, Iran. In addition they can send email to ebrahimi_masood@yahoo.com or ma.ebrahimi@uok.ac.ir.

Contents

CCHP Literature

1

1.1 Introduction

Conventional separate production of cooling, heating, and power has been used since the first power plant was built in 1878.[1] In this book it is called SCHP (separate production of cooling, heating, and power). In SCHP, electricity is generated in conventional centralized big power plants that can produce hundreds of megawatts of electricity. Then it is transmitted and distributed through the electricity grid to feed the terminal consumers in different sectors, such as residential, industrial, commercial, etc. The heating and cooling demands of the terminal consumers are provided by the grid electricity, combustion of fossil fuels, and/or renewable energy resources such as the sun, geothermal resources, etc.

On the contrary, in the combined production of cooling, heating and power, which in this book it is called CCHP,[2] electricity is generated in the vicinity of the consumer, and the waste heat of the power generation unit can be recovered to produce heating or cooling when the need arises. Due to generation of electricity in the vicinity of the consumer, the transmission and distribution losses (T&D losses) are omitted.[3] The CCHP system increases the energy efficiency by recovering heat loss and omitting grid loss. A schematic of the SCHP and CCHP systems are presented in Figure 1.1. In the SCHP system, electricity is received from the grid. The overall efficiency of the power plant, transmission, and distribution grid is assumed to be 30%, heating is provided by a boiler with the effectiveness $\varepsilon = 80\%$, and cooling is provided by an absorption chiller with a coefficient of performance (COP) of 0.7. In the CCHP unit however, electricity is provided by the prime mover, heating is prepared by recovering the waste heat, and cooling is produced by using the recovered heat in the absorption chiller. The figure shows that to provide the same demands for a building the CCHP overall efficiency can be as much as 30% higher than the SCHP; in addition the CCHP consumes 37.76% less fuel than SCHP. This higher efficiency means considerable fuel savings and pollution reduction, leading to more economically efficient system.

CCHP systems have additional advantages. They are less fragile than centralized power plants when natural disasters such as earthquakes occur. Because they are distributed, they can run independently from the grid and also can be designed to run with different fuels. They are also less sensitive to terrorist attacks or war, because it is almost impossible to attack all of the CCHP systems. A study after the September 11th

[1]The world's first power plant was built and designed by Sigmund Schuckert in the Bavarian town of Ettal and went into operation in 1878. The station consisted of 24 dynamo electric generators, which were driven by a steam engine.

[2]In some research the CCHP concept is also called trigeneration.

[3]A major vendor of superconducting conductors claims that the HTS cable losses are only half a percent (0.5%) of the transmitted power compared to 5-8% for traditional power cables. Source: www.nema.org.

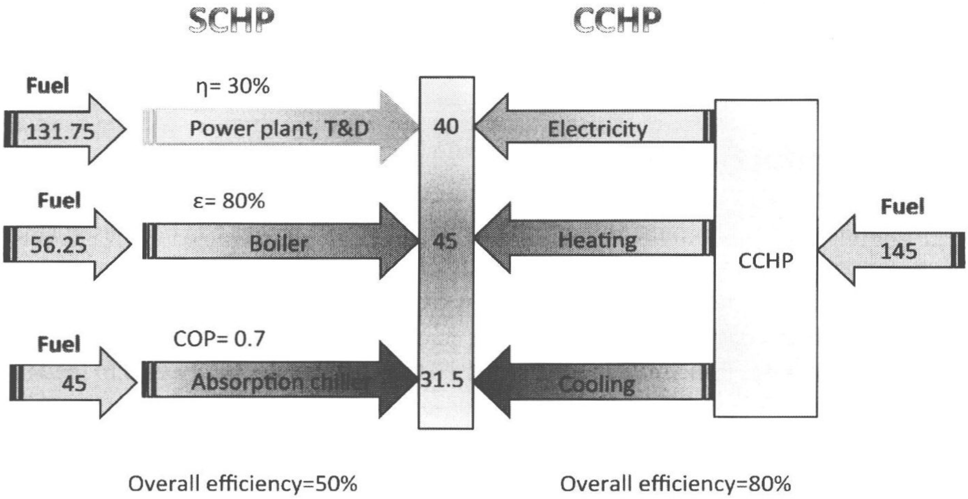


Figure 1.1 Comparison between SCHP and CCHP systems.

terrorist attacks suggested that a system based on distributed generation plants may be five times less sensitive to systematic attack than a centralized power system [8].

In addition, a CCHP system can make money if well designed and managed. A CCHP system can earn money by saving fuel and selling the surplus electricity to the grid. According to the research, a payback period of less than five years is achievable for systems that can work at least 15 years. This means the CCHP system produces significant economic benefits in the last 10 years of its life.

The advantages of CCHP systems make them a very good solution for those who care about energy resources, the Earth's environment, air pollution, greenhouse gases, and safety of power generation, transmission and distribution. To help in utilizing these advantages, this book is prepared as a guideline for the decision-making process for CCHP system and their design and optimization. In this chapter a literature review of CCHP systems highlighting the last decade will be presented. In this review we have focused on the different CCHP cycles and evaluation criteria used by researchers.

1.2 CCHP in the Last Decade

In order to be familiar with the advances of and recent research about CCHP systems, we have done a review of the published research in the last decade. In this literature review, we have focused on different CCHP cycles, which are presented numerically and/or experimentally. In addition, the design criteria and considerations for each CCHP cycle are also summarized. This review shows how the energy or waste energy is used in different CCHP technologies. It also draws a comprehensive picture of the technologies that are currently used or being actively researched for use in CCHP systems. This review starts in 2002 and will help researchers, designers, and students become familiar with the concept of CCHP very quickly and accelerate their learning.

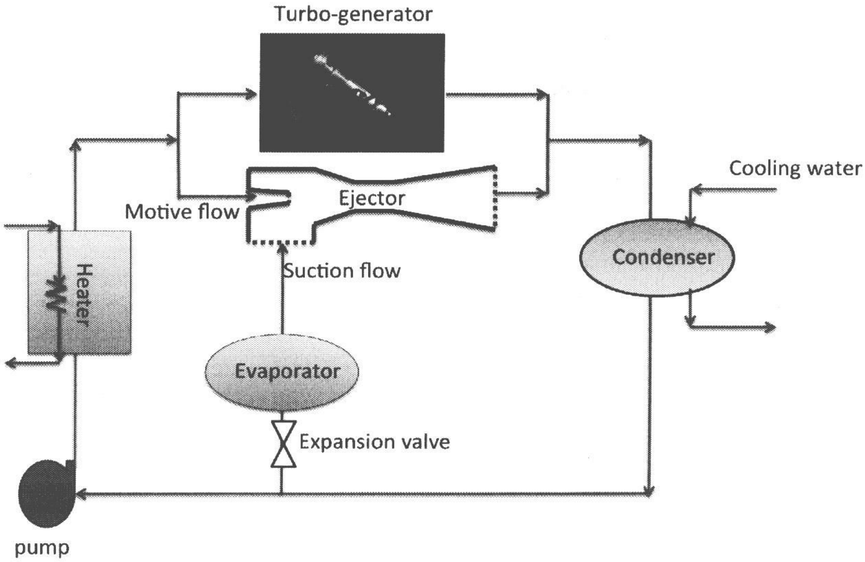


Figure 1.2 The CCHP cycle and the mini turbo-generator proposed by [1].

In 2002, Ref. [1] presented an empirical work involving an ejector heat pump coupled with a Rankine cycle that was proposed to meet the heating, cooling, and electricity demands of a residential building. The cycle was designed to use solar energy or natural gas as the input energy resource. In Figure 1.2 the cycle and the mini turbo-generator used in this experiment are presented.

In the cycle presented in Figure 1.2, the impact of the three working fluids n-pentane, water, and R134a on the coefficient of performance (COP) of the cooling cycle was investigated. Two prototypes with cooling capacities of 2 and 5 kW were built. The nominal output power of the turbo-generator was 1.5 kW and water was used for its cooling. One of the cycles was equipped with a 20 m^2 solar collector to be used in the UK, and the other one used natural gas as the fuel and operated in Portugal. The results show a mean COP of 0.3, and electrical efficiency of 3% to 4% in ambient temperature of 20°C. The boiler temperature in these experiments was 95°C, pump and fan consumption was negligible, and turbine efficiency due to frictional loss and water cooling was 28%. This research concludes that improvement of turbine technology has a significant impact on cycle performance. The cycle also shows improvement in CO_2 reduction in comparison with conventional systems, which consume coal as the fuel. This research also defined an economic criterion called *cost figure (CF)* as follows:

$$CF = \frac{capital\ cost + running\ cost + maintenance\ cost}{(energy\ delivered/year) \times number\ of\ years}\ (\text{euro/kW h}) \tag{1-1}$$

The results showed that the economic criterion improves when the cycle is used for trigeneration rather than power and cooling generation only. They also concluded that the cycle is especially economical when the cooling load is high and the cycle is used to provide domestic hot water (DHW) as well. While Ref. [1] concluded that promotion of small- and micro-scale turbines is necessary to improve performance of CCHP systems, Ref. [2] in 2002 reported the characteristics of micro gas turbines (MGTs), and also presented the main producers of MGTs around the world. This reference also reports that among different applications of MGTs, the most popular use is in combined heating and power (CHP) systems, because it has a high-quality exhaust gas that makes it very suitable for district heating.

In 2003, Ref. [3] considered some hotels in the Euro zone and based on the hotels' demands designed the main components of a CCHP system including the prime mover and absorption chiller. The design criteria of the CCHP system that they considered include an energy utilization factor (EUF), artificial thermal efficiency (ATE), fuel energy savings ratio (FESR), and exergy efficiency (π). These criteria are defined as follows:

$$EUF = \frac{E_{PM} + H_{dem}}{F_{CCHP}} \tag{1-2}$$

$$ATE = \frac{E_{PM}}{F_{CCHP} - \frac{H_{dem}}{\eta_b}} \tag{1-3}$$

$$FESR = 1 - \frac{F_{CCHP}}{\frac{H_{dem}}{\eta_b} + \frac{E_{PM}}{\eta_{e,pp}}} \tag{1-4}$$

$$\pi = \frac{E_{PM} + \dot{\phi}_H}{\dot{\phi}_{in,CCHP}} \tag{1-5}$$

In the above equations it is assumed that the recoverable heat from the prime mover satisfies the heat demand (H_{dem}) of the building, and E_{PM} is the kW of electricity that is generated by the prime mover under full load or partial load operation. In addition, H and η stand for heating and efficiency, respectively. Also the subscripts of *PM*, *in*, *pp*, *dem*, *b*, and *e* mean prime mover, input, conventional power plant, demand, boiler, and electrical, respectively. Moreover, H_{dem} represents the heating load plus DHW load. In addition if there is simultaneous heating and cooling, H_{dem} represents summation of the heating load, the DHW load, and the heat required to operate the absorption chiller. The authors concluded that because the *FESR* and π consider different magnitudes and types of energy demand, they can show the real behavior of the CCHP system much better.

However, the above criteria are not enough for designing a CCHP system, because these criteria do not consider the impact of different energy management methods.

Reference [3] compares two energy management strategies of *thermal demand management* (TDM) and management of *primary energy savings* (PES). The first method is also called *following thermal demand* (FTL) in which preparing the thermal demand is the top priority for the CCHP system and must be satisfied by the designed CCHP system; this means that if the electricity production of the CCHP system does not fulfill the electrical demand of the building, the lack of electricity would be compensated for by the electricity grid. The PES method, which is the main proposal of Ref. [3], sets a constraint to ensure the energy savings of the CCHP in the working period as follows:

$$Fuel_{CCHP} \leq \frac{H_{dem} \cdot \eta_{e,pp}}{\eta_b(\eta_{e,pp} - \eta_{e,CCHP})} \tag{1-6}$$

Based on the PES strategy proposed by [3] the engine operates in full load as long as the FESR is positive and energy saving occurs.

The above equation does not consider the grid loss. Since the electricity loss due to transmission and distribution (T&D losses) of electricity is significant and may reach as high as 10% in some countries, we recommend counting it. Therefore for better judgment the following equation is suggested for yearly calculations when the CCHP system follows the thermal load (FTL):

$$\sum_{yearly} F_{pp} + \sum_{yearly} F_b \geq \sum_{yearly} F_{CCHP} \tag{1-7}$$

Substituting the equivalent expressions in the above equation and bearing in mind that the CCHP considered here follows the FTL strategy results in the following:

$$\sum_{yearly} \frac{E_{PM}}{\eta_{e,\,pp}\eta_g} + \sum_{yearly} \frac{H_{dem}}{\eta_b} \geq \sum_{yearly} F_{CCHP} \tag{1-8}$$

$$\sum_{yearly} \frac{\eta_{e,CCHP} F_{CCHP}}{\eta_{e,pp}\eta_g} + \sum_{yearly} \frac{H_{dem}}{\eta_b} \geq \sum_{yearly} F_{CCHP} \tag{1-9}$$

and finally

$$\sum_{yearly} F_{CCHP} \leq \frac{\sum_{yearly} H_{dem}}{\left(1 - \frac{\eta_{e,\,CCHP}}{\eta_{e,\,pp} \cdot \eta_g}\right)\eta_b} \tag{1-10}$$

In the above equation it is assumed that the prime mover electrical efficiency remains constant in PLO and is equal to its nominal efficiency.

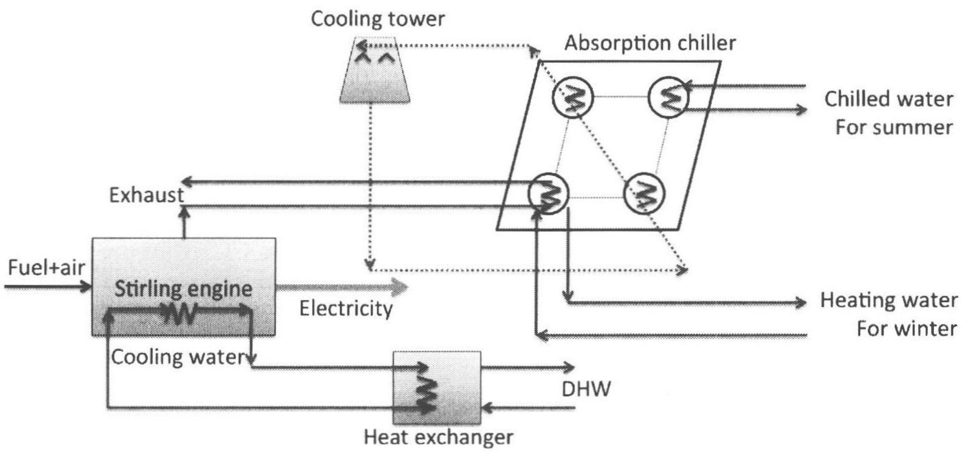


Figure 1.3 Schematic of the Stirling engine–based CCHP system proposed by [4].

Reference [3] used the maximum rectangle method (MRM) to size the CCHP components. In 2004, Ref. [4] presented some simulations for a CCHP system that was designed based on a Stirling engine. The cycle is shown in Figure 1.3.

As can be seen this cycle uses an absorption chiller for cooling purposes. The exhaust heat is used to run the chiller in cooling mode and prepare heating load for the summer mode. The base load, which is the DHW load, is prepared in a heat exchanger by the cooling water of the compression side of the Stirling engine. To investigate the applicability of this CCHP, primary energy savings (PES), primary energy rate (PER), and the economic criteria annual saving cost (AS), annual avoided cost (AC), and payback period (PB) are evaluated. The PER is defined as follows:

$$PER_{CCHP} = \frac{\sum_{yearly} F_{CCHP}}{\sum_{yearly} (H_{CCHP} + C_{CCHP} + DHW_{CCHP} + E_{PM})} \tag{1-11}$$

Hence, the PER is the ratio of annual fuel consumption of the CCHP system to the annual summation of useful energy outputs from the CCHP system including heating, cooling, DHW, and electricity. It is clear the smaller the PER the better the CCHP system.

Annual avoided cost (AC) is defined as the summation of all costs that are not paid when using CCHP system but are paid when using SCHP:

$$AC = \sum_{yearly} (i_C C_{CCHP} + i_H H_{CCHP} + i_{DHW} DHW_{CCHP} + i_E E_{PM}) \tag{1-12}$$

where i is the index price of buying energy. Reference [4] defines AS as follows:

$$AS = AC - I_{OM} - \sum_{yearly} i_{Fuel} F_{CCHP} \tag{1-13}$$