MODELLING AND ANALYSIS OF BUILDING SYSTEMS THAT INTEGRATE COGENERATION AND DISTRICT HEATING AND COOLING

Marc A. Rosen Wey H. Leong Minh N. Le
Department of Mechanical, Aerospace and Industrial Engineering
Ryerson University
Toronto, Ontario, M5B 2K3, Canada
mrosen@ryerson.ca weyleong@ryerson.ca

ABSTRACT

The modelling and analysis of building systems that integrate cogeneration and district heating and cooling are described. The analysis work uses exergy methods, in addition to the more conventional energy analysis, to evaluate overall and component efficiencies and to identify and assess thermodynamic losses. Exergy analysis is a relatively new analysis technique that provides enhanced understanding of the characteristics of energy systems and can assist design and improvement efforts. The modelling efforts focus on simplified models that can be assessed relatively straightforwardly and facilitate the application of simulation tools. The use of thermal energy storage and the impact of heat losses in the ground are considered. The latter can be significant for the system components that can be on- or below-ground, including the buildings, any present thermal storage and the district heating and/or cooling piping. The results should assist in the enhancement of simulation techniques for building energy systems.

INTRODUCTION

This paper considers integrated energy systems in buildings, including such technologies as cogeneration, district heating and cooling, and thermal energy storage. Such building energy systems can be complex, relative to conventional systems, in that integrated systems often carry out the provision of electrical, heating and cooling services simultaneously.

Two particular aspects of the modelling, simulation and design of such building energy systems are emphasized in this paper:

- the benefits of using exergy analysis in such activities, and
- the difficulties in dealing with systems involving many in-ground components (e.g., underground distribution pipes in district heating and cooling networks, and underground thermal energy storages).

Rather than focus exclusively in this paper on the simulation of building energy systems, we concentrate more on modelling activities, bearing in mind the fact that the resulting models can be incorporated into simulation codes. Also, analyses based on exergy methods can be incorporated into simulation codes.

In this paper, consequently, the following topics are covered:

- background on exergy analysis and its use in simulation codes,
- efficiency analysis of a system design for an integrated building energy system, and
- discussion of the aspects of such systems involving in-ground components, and how they can be dealt with.

The objectives of this paper are to improve understanding of (i) models for whole building simulation, (ii) the benefits of using exergy analysis in such work, and (iii) the need to consider carefully heat transfer through the ground in systems where extensive use is made of in-ground components. It is anticipated that the work will assist developers and users of simulation tools for building systems.

BACKGROUND ON EXERGY METHODS

Energy and exergy analyses (Moran and Sciubba, 1994; Moran and Shapiro, 2000; Kotas, 1995) are used to perform thermodynamic performance comparisons in the present study. Energy analysis is based on the first law of thermodynamics, which is concerned with the conservation of energy. Exergy analysis is based on the second law, and generally allows process inefficiencies to be better pinpointed than does an energy analysis, and efficiencies to be more rationally evaluated. Many researchers propose that the thermodynamic performance of a process is best evaluated with exergy analysis.

Exergy is defined as the work which can be produced by a stream or system as it is brought into equilibrium with a reference environment, and can be thought of as a measure of the quality (or usefulness) of energy, work having the highest quality. In simple terms, exergy is that portion of energy that is available for performing useful tasks. Exergy is consumed during real processes, and conserved during ideal processes. The exergy consumption during a process is proportional to the entropy created due to process irreversibilities.

Applications of exergy analysis have increased in recent years, and have included investigations of electricity generation and cogeneration (Moran and Shapiro, 2000; Kotas, 1995; Rosen and Le, 1998; Rosen and Berry, 1989; Rosen and Scott, 1985). For conventional energy technologies, energy and exergy analyses have been performed and have yielded useful results. For advanced energy technologies, the use of energy and exergy analyses can be expected to provide meaningful insights into performance that will assist in achieving optimal designs.

EXERGY AND SIMULATION

The second law of thermodynamics is often not considered in modelling and simulation. The present authors believe the lack of second-law considerations is one of the main weaknesses of simulators. Violations of the second law sometimes occur in modelling and simulation (e.g., thermal energy passing of itself from a lower to a higher temperature, and entropy being consumed in a system) if only the first law is considered.

One of the present authors has enhanced two process-simulation computer codes, Aspen Plus and Salt, for exergy analysis (Rosen and Berry, 1989; Rosen and Scott, 1985). The enhancements and their applications are detailed elsewhere (Rosen and Berry, 1989; Rosen and Scott, 1985). It is expected that similar enhancements for exergy analysis can be made to simulation codes for building energy systems.

MODELLING AND ANALYSIS OF A WHOLE BUILDING SYSTEM

Edmonton Power proposed for downtown Edmonton, Alberta, Canada a major cogeneration-based district heating and cooling project having (Edmonton Power, 1991): (i) an initial supply capacity of 230 MW(thermal) for heating and 100 MW(thermal) for cooling, with the potential to expand to about 400 MW(thermal) for heating over the next ten years; (ii) the capacity to displace about 15 MW of electrical power used for electric chillers through district cooling; and (iii) the potential to increase the efficiency of the Rossdale power plant that would provide the steam for district heating and cooling from about 30% to 70%. The design incorporated central chillers and a district cooling network. Screw chillers were to be used originally, and absorption chillers in the future.

This section is based on previous research by the authors (Rosen and Le, 1998) in which the Edmonton Power design for cogeneration-based district heating (using a district heating network and heat exchangers) and district cooling (using central, electrically-driven centrifugal chillers and a district cooling network) was modelled and evaluated thermodynamically. Then, the design was modified by replacing the electric centrifugal chillers with heat-driven absorption chillers, and the evaluation was repeated.

The intent of the present work, in part, is to reveal insights that will aid the designers of such systems in simulation and optimization activities, and in the selection of the proper type of systems for different applications and situations. It is hoped that the present results will permit energy utilities to improve existing plants where appropriate, and to develop better designs.

A second motivating factor in the present work relates to some of the difficulties associated with the types of analysis tools often used for cogeneration/district energy systems. In general, energy technologies are normally examined thermodynamically using energy analysis, although a better understanding is attained when a more complete thermodynamic view is taken. Exergy analysis provides an additional thermodynamic perspective and, in conjunction with energy analysis, permits the performance of more complete thermodynamic analyses. Consequently, both energy- and exergy-based approaches to thermodynamic analysis are considered in this study, both to improve the quality of the results and to demonstrate the usefulness of exergy analysis.

Approach and Methodology

There are two main stages in this study. First, the Edmonton Power design for cogeneration-based district heating and cooling is modelled and evaluated. The system is shown in Figure 1. Then, the design is modified by replacing the electric centrifugal chillers with heat-driven absorption chillers (single- and double-effect types), and re-examined. The modified portion of the system is shown in Figure 2.

The plant is divided into six major components for modelling and analysis purposes. Efficiencies of the individual components and the overall cogeneration-based district energy system are examined. Also, several subsystems, comprised of selected combinations of the components, are evaluated to pinpoint better the locations and causes of inefficiencies. Both energy and exergy analyses are used throughout the thermodynamic assessments.

For simplicity, economics and part-load operation are not considered in the present understanding. The results and findings are thus correspondingly limited. Also, several simplifying energy-related assumptions are used to keep the paper concise and direct, while still permitting the differences between the energy and exergy results to be highlighted.

Annual energy transfer rates for the cogeneration-based district energy system are shown in Table 1, with details distinguished for the three chiller options considered. The data in Table 1 are used to calculate energy and exergy efficiencies of the systems for the year and for winter (October to April) and summer (May to September) periods.

Analyses of System Components

Cogeneration of Electricity and Heat

The electricity production rate $\dot{W}$ can be expressed for a cogeneration-based system using electric chillers as a function of the product-heat generation rate $\dot{Q}_H$ as

$$\dot{W} = \left(\frac{\eta_{elec}^{CHP}}{\eta_{heat}^{CHP}}\right)\dot{Q}_H \tag{1}$$

and for a cogeneration-based system using absorption chillers as a function of the product-heat generation rates, $\dot{Q}_H$ and $\dot{Q}_{gen}$, as

$$\dot{W} = \left(\frac{\eta_{elec}^{CHP}}{\eta_{heat}^{CHP}}\right)\left(\dot{Q}_H + \dot{Q}_{gen}\right) \tag{2}$$

where η_{elec}^{CHP} and η_{heat}^{CHP} denote respectively the electrical and heat efficiencies of the cogeneration, or combined heat and power (CHP), plant. The total energy efficiency can be written for cogeneration using electric chillers as

$$\eta_{tot}^{CHP} = \frac{\dot{W} + \dot{Q}_H}{\dot{E}_f} \tag{3}$$

and for cogeneration using absorption chillers as

$$\eta_{tot}^{CHP} = \frac{\dot{W} + \dot{Q}_H + \dot{Q}_{gen}}{\dot{E}_f} \tag{4}$$

where $\dot{E}_f$ denotes the fuel energy input rate. The corresponding total exergy efficiency can be expressed for cogeneration using electric chillers as

$$\psi_{tot}^{CHP} = \frac{\dot{W} + \tau_{Q_H}\dot{Q}_H}{\left(R\dot{E}\right)_f} \tag{5}$$

and for cogeneration using absorption chillers as

$$\psi_{tot}^{CHP} = \frac{\dot{W} + \tau_{Q_H}\dot{Q}_H + \tau_{Q_{gen}}\dot{Q}_{gen}}{\left(R\dot{E}\right)_f} \tag{6}$$

where τ_{Q_H} and $\tau_{Q_{gen}}$, respectively, are the exergetic temperature factors for $\dot{Q}_H$ and $\dot{Q}_{gen}$. For heat transfer at a temperature T, $\tau \equiv 1 - T_o/T$ (Moran and Shapiro, 2000; Kotas, 1995), where T_o denotes the environmental temperature. Here, R denotes the energy grade function, values of which for most fossil fuels are between 0.9 and 1.0 (Moran and Shapiro, 2000; Kotas, 1995).

Chilling

Edmonton Power has annual free cooling of 33 GWh/yr; the cooling requirement of the chilling plant is 169 GWh/yr. The *COP* of the centrifugal chiller in the design is 4.5 (Edmonton Power, 1991). Thus, the annual electricity supply rate to the chiller is $\dot{W}_{ch}$ = 169/4.5 = 38 GWh/yr. For the chilling operation, including free cooling and electrical cooling, *COP* = (169 + 33)/38 = 5.32. The net electricity output ($\dot{W}_{net}$) of the combined cogeneration/chiller portion of the system is 433 – 38 = 395 GWh/yr, where the electrical generation rate of the cogeneration plant is 433 GWh/yr. Similarly, the coefficient of performance for the chilling operation, including free cooling, using single-effect absorption cooling is *COP* = 202/252 = 0.80, and using double-effect absorption cooling is *COP* = 202/141 = 1.43. It is noted for the absorption chiller cases that, since the work required to drive the solution and refrigeration pumps is very small relative to the heat input (often less than 0.1%), this work is neglected here.

The exergy efficiency can be written for the chilling operation using electric chillers as

$$\psi_{ch} = \frac{-\tau_{QC}\dot{Q}_C}{\dot{W}_{ch}} \tag{7}$$

and using absorption chillers as

$$\psi_{ch} = \frac{-\tau_{Q_C}\dot{Q}_C}{\tau_{Q_{gen}}\dot{Q}_{gen}} \tag{8}$$

Transport of Heat and Cool

District heating utilizes hot water supply and warm water return pipes, while district cooling utilizes cold water supply and cool water return pipes. The pipes are assumed here to be perfectly insulated so that heat loss or infiltration during fluid transport can be neglected. Hence, the energy efficiencies of the district heating and cooling portions of the system are both 100%. The exergy efficiency can be evaluated for district heating as

$$\psi_{DH} = \frac{\tau_{Q_H^u}\dot{Q}_H^u}{\tau_{Q_H}\dot{Q}_H} \tag{9}$$

and for district cooling as

$$\psi_{DC} = \frac{-\tau_{Q_C^u}\dot{Q}_C^u}{-\tau_{Q_C}\dot{Q}_C} \tag{10}$$

Utilization of Heat and Cool

Heat loss and infiltration for the end-use heating and cooling components are assumed negligible here so that their energy efficiencies are 100%. The exergy efficiency can be expressed for end-use heating as

$$\psi_{UH} = \frac{\tau_{Q_H^{u,s}}\dot{Q}_H^{u,s} + \tau_{Q_H^{u,w}}\dot{Q}_H^{u,w}}{\tau_{Q_H^u}\dot{Q}_H^u} \tag{11}$$

and for end-use cooling as

$$\psi_{UC} = \frac{-\tau_{Q_C^{u,r}}\dot{Q}_C^{u,r}}{-\tau_{Q_C^u}\dot{Q}_C^u} \tag{12}$$

The left and right terms in the numerator of Eq. 11 represent the thermal exergy supply rates for space and hot-water heating, respectively.

Analysis of Overall System

Since there are three different products generated (electricity, heat and cool), application of the term energy efficiency here is prone to be misleading (Rosen and Le, 1995), in part for the same reason that "energy efficiency" is misleading for a chiller. Here, an overall-system "figure of merit" f_{sys} is used, and calculated as follows (Rosen and Le, 1995):

$$f_{sys} = \frac{\dot{W}_{net} + \dot{Q}_H^{u,s} + \dot{Q}_H^{u,w} + \dot{Q}_C^{u,r}}{\dot{E}_f} \tag{13}$$

The corresponding exergy-based measure of efficiency is simply an exergy efficiency, and is evaluated as

$$\psi_{sys} = \frac{\dot{W}_{net} + \tau_{Q_H^{u,s}}\dot{Q}_H^{u,s} + \tau_{Q_H^{u,w}}\dot{Q}_H^{u,w} - \tau_{Q_C^{u,r}}\dot{Q}_C^{u,r}}{\left(R\dot{E}\right)_f} \tag{14}$$

Results and Discussion

Efficiencies of the overall cogeneration-based district energy system, for the three chiller cases considered, are presented in Table 2. The efficiencies for the heating and cooling sides of the overall system are also presented in Table 2. The overall energy efficiencies are seen to vary, for the three system alternatives considered, from 83 to 94%, and exergy efficiencies from 28 to 30%.

The results demonstrate that energy efficiencies do not provide meaningful and comparable results relative to exergy efficiencies when the energy products are in different forms. For example, the energy efficiency of the overall process using electric chillers is 94%, which could lead one to believe that the system is very efficient. The exergy efficiency of the overall process, however, is 28%, indicating that the process is far from ideal thermodynamically. The exergy efficiency is much lower than the energy efficiency in part because heat is being produced at a temperature (120°C) higher than the temperatures actually needed (22°C for space heating and 40°C for hot-water heating). The low exergy efficiency of the chillers is largely responsible for the low exergy efficiency for the overall process.

The exergy efficiencies of the cooling side of the system are relatively low, ranging from 9% to 14% (Table 2). These low efficiency value can be explained by noting that the cool-water supply temperature (11°C) needed for space cooling (to 22°C) is relatively near to the environmental temperatures (in summer). The exergy of the cool is small compared with the work input to drive the electric centrifugal chiller. The excess exergy input via work is destroyed due to irreversibilities.

The exergy-based efficiencies in Table 2 are generally different than the energy-based ones because the energy efficiencies utilize energy quantities which are in different forms, while the exergy efficiencies provide more meaningful and useful results by evaluating the performance and behaviour of the systems using work equivalents for all energy forms. The exergy and energy for electricity are the same while the exergy for the thermal energy forms encountered here is less than the corresponding energy.

The results for cogeneration-based district energy systems using absorption chillers (single-effect and double-effect types) and using electric chillers are, in general, similar. Generally, the results appear to indicate that the three integrated cogeneration and district energy systems considered have similar efficiencies. It is likely, therefore, that the choice of one option over another will be strongly dependent on economics and other factors (e.g., environmental impact, space availability, noise limitations, etc.).

MODELLING OF IN-GROUND BUILDING SYSTEM COMPONENTS

The impact is considered of heat losses in the ground, which can be significant for system components that are on- or in-ground.

Heat and Moisture Transport in Ground

Heat and moisture transport in ground is a complex phenomenon. The governing equations are coupled and usually must be solved simultaneously using numerical methods. A computer model based on finite element methods, called G-HEADS (Tarnawski and Leong, 1990), has been developed for analyzing ground thermal energy storage with a ground heat exchanger. The performance of a ground-coupled heat pump system depends strongly on the moisture content and the soil type (Leong, Tarnawski and Aittomäki, 1998). Besides the natural variation of soil moisture content throughout a year, moisture variation in ground can be further augmented by the temperature gradients due to heat extraction and deposition, leading to significant change in soil thermal properties. With modifications, G-HEADS can be used for predicting thermal energy and exergy losses or gains for district pipes in the ground within a heating or cooling season.

District Heating and Cooling

District heating utilizes hot water supply and warm water return pipes, while district cooling utilizes cold water supply and cool water return pipes. The pipes can be on or below ground. For a realistic analysis, the heat loss or gain during fluid transport should be considered, even if the pipes are insulated. Hence, the energy efficiencies of the district heating and cooling portions of the system are both actually less than 100%. The thermal interaction between heating/cooling pipe and ground can be very complex. A dynamic simulation of the process should include weather data for the ground-air boundary interaction and soil thermal and hydraulic properties for heat and moisture transport in soils. The exergy efficiency can be evaluated by extending Eqs. 9 and 10 to account for thermal losses/gains for district heating as

$$\psi_{DH} = \frac{\tau_{Q_H^u}\,\dot{Q}_H^u - \tau_{Q_H^l}\,\dot{Q}_H^l}{\tau_{Q_H}\,\dot{Q}_H} \tag{15}$$

and for district cooling as

$$\psi_{DC} = \frac{-\tau_{Q_C^u}\,\dot{Q}_C^u + \tau_{Q_C^g}\,\dot{Q}_C^g}{-\tau_{Q_C}\,\dot{Q}_C} \tag{16}$$

The right terms in the numerator of Eqs. 15 and 16 represent the piping thermal exergy loss and gain in the ground, respectively.

The corresponding exergy-based measure of efficiency is simply an overall system exergy efficiency, and is evaluated by similarly extending Eq. 14 as

$$\psi_{sys} = \frac{\begin{pmatrix} \dot{W}_{net} + \tau_{Q_H^{u,s}}\,\dot{Q}_H^{u,s} + \tau_{Q_H^{u,w}}\,\dot{Q}_H^{u,w} \\ -\tau_{Q_C^{u,r}}\,\dot{Q}_C^{u,r} - \tau_{Q_H^l}\,\dot{Q}_H^l + \tau_{Q_C^g}\,\dot{Q}_C^g \end{pmatrix}}{\left(R\dot{E}\right)_f} \tag{17}$$

Thermal Energy Storage

Building energy systems may involve thermal energy storage. For example, a ground-coupled heat pump system can extract low-grade heat, which may be deposited in the ground during summer using the waste heat from a central chiller and/or by natural means, for space heating in winter. This low-grade heat can also be extracted using a heat pump for domestic hot water during both winter and summer. Utilizing thermal energy storage may increase energy and exergy efficiencies of building energy systems.

LONG-TERM RESEARCH NEEDS

Two key areas of research related to building energy systems and their simulation that appear to be needed emanate from the present work:

- the inclusion of exergy methods in building energy system simulation, and
- better accounting for the heat losses associated with in- or on-ground components of whole building systems.

CONCLUSIONS

This work has helped improve our understanding of the efficiencies of the components that comprise an integrated system for cogeneration and district energy.

In particular, exergy analysis provides important insights into the performance and efficiency. The present results indicate that the complex array of energy forms involved in cogeneration-based district energy systems make them difficult to assess and compare thermodynamically without exergy analysis. This difficulty is primarily attributable to the different nature and quality of the three product energy forms: electricity, heat, and cool. The difficulties in dealing with systems involving many in-ground components (e.g., underground distribution pipes in district heating and cooling networks, and underground thermal energy storages) have also examined. The results are expected to aid designers of such systems in development and optimization activities, and to assist developers and users of simulation tools for building systems.

ACKNOWLEDGMENTS

Financial support was provided by the Natural Sciences and Engineering Research Council of Canada.

NOMENCLATURE

COP	coefficient of performance
E	energy
f	figure of merit
Q	heat
T	temperature
W	work
R	energy grade function
η	energy efficiency
τ	exergetic temperature factor
ψ	exergy efficiency

Subscripts

C	cooling
ch	chiller
DH	district heating
DC	district cooling
$elec$	electrical
f	fuel
gen	generator of absorption chiller
H	heating
$heat$	heat
net	net
o	environmental state
sys	system
tot	total
UH	end-use heating
UC	end-use cooling

Superscripts

$\cdot$	rate with respect to time
CHP	combined heat and power (cogeneration)
g	gain
l	loss
r	room
s	space
u	end-use
w	water

REFERENCES

Edmonton Power (1991) (approx.), City of Edmonton District Energy Development Phase, Section 2: Engineering Report.

Kotas, T.J. (1995), *The Exergy Method of Thermal Plant Analysis*, reprint edition, Krieger, Malabar, Florida.

Leong, W.H., Tarnawski, V.R. and Aittomäki, A. (1998), 'Effect of Soil Type and Moisture Content on Ground Heat Pump Performance', *Int. J. Refrig.*, 21, 595-606.

Moran, M.J. and Sciubba, E. (1994), 'Exergy Analysis: Principles and Practice,' *J. Engineering for Gas Turbines and Power*, 116, 285-290.

Moran, M.J. and Shapiro, H.N. (2000), *Fundamentals of Engineering Thermodynamics,* 4th ed., Wiley, New York.

Rosen, M.A. and Berry, G.F. (1989), 'The Enhancement of the SALT Simulation and Analysis Code for First- and Second-Law Analysis.' In *Thermodynamic Analysis and Improvement of Energy Systems*, ed. Cai Ruixian and M.J. Moran, Pergamon, Toronto, 472-480.

Rosen, M.A. and Le, M.N. (1995), 'Efficiency Measures for Processes Integrating Combined Heat and Power and District Cooling.' In *Thermodynamics and the Design, Analysis and Improvement of Energy Systems*, AES-Vol. 35, ASME, New York, 423-434.

Rosen, M.A. and Le, M.N. (1998), 'Thermodynamic Assessment of the Components Comprising an Integrated System for Cogeneration and District Heating and Cooling.' In *Proc. ASME Advanced Energy Systems Division*, AES-Vol. 38, ASME, New York, 3-11.

Rosen, M.A. and Scott, D.S. (1985), 'The Enhancement of a Process Simulator for Complete Energy-Exergy Analysis.' In *Analysis of Energy Systems - Design and Operation*, AES-Vol. 1, ASME, New York, 71-80.

Tarnawski, V.R. and Leong, W.H. (1990), *Computer Simulation of Ground Coupled Heat Pump Systems*, Report submitted to National Research Council, Ottawa.

Table 1. Annual Energy Transfer Rates (in GWh) for the Cogeneration-Based District Energy System[1]

Type of energy	Winter period, T_o = 0°C	Summer period, T_o = 30°C
District heating, $\dot{Q}_H$	$0.8946 \times 1040 = 930$	$0.1054 \times 1040 = 110$
Water heating, $\dot{Q}_H^{u,w}$	(22 GWh/yr/mo.) × 7 mo. = 154	$0.1054 \times 1040 = 110$
Space heating, $\dot{Q}_H^{u,s}$	$930 - 154 = 776$	0
Space cooling, $\dot{Q}_C$	0	$1.00 \times 202 = 202$
Electric chiller case		
Total electricity, $\dot{W}$	$0.8946 \times 433 = 388$	$0.1054 \times 433 = 45.6$
Input energy, $\dot{E}_f$	$0.8946 \times 1733 = 1551$	$0.1054 \times 1733 = 183$
1-stage absorption chiller case		
Heat to drive absorption chiller, $\dot{Q}_{gen}$	0	$1.00 \times 252 = 252$
Total electricity, $\dot{W}$	$0.8946 \times 433 = 388$	$25/60(110 + 252) = 151$
Input energy, $\dot{E}_f$	$0.8946 \times 1733 = 1551$	$(110 + 252)/0.6 = 603$
2-stage absorption chiller case		
Heat to drive absorption chiller, $\dot{Q}_{gen}$	0	$1.00 \times 141 = 141$
Total electricity, $\dot{W}$	$0.8946 \times 433 = 388$	$21/64 \times (110 + 141) = 82$
Input energy, $\dot{E}_f$	$0.8946 \times 1733 = 1551$	$(110 + 141)/0.64 = 391$

[1] The winter period (October-April) accounts for 89.46% of the annual heating load and 0% of the annual cooling load, and the summer period (May-September) for the remaining annual heating and cooling loads.

Table 2. Overall and Subsystem Efficiencies for the Cogeneration-Based District Energy System

Subsystem	Energy efficiency, η (%)			Exergy efficiency, ψ (%)		
	Centrifugal chiller	1-stage absorption chiller	2-stage absorption chiller	Centrifugal chiller	1-stage absorption chiller	2-stage absorption chiller
Heating side[1]	85	85	85	30	31	31
Cooling side[2]	532[3]	80[3]	143[3]	14	9	12
Overall system	94	83	88	28	29	29

[1] The heating side includes cogeneration, district heating and end-use heating.

[2] The cooling side includes chilling, district cooling and end-use cooling.

[3] These are coefficient of performance (*COP*) values when divided by 100.

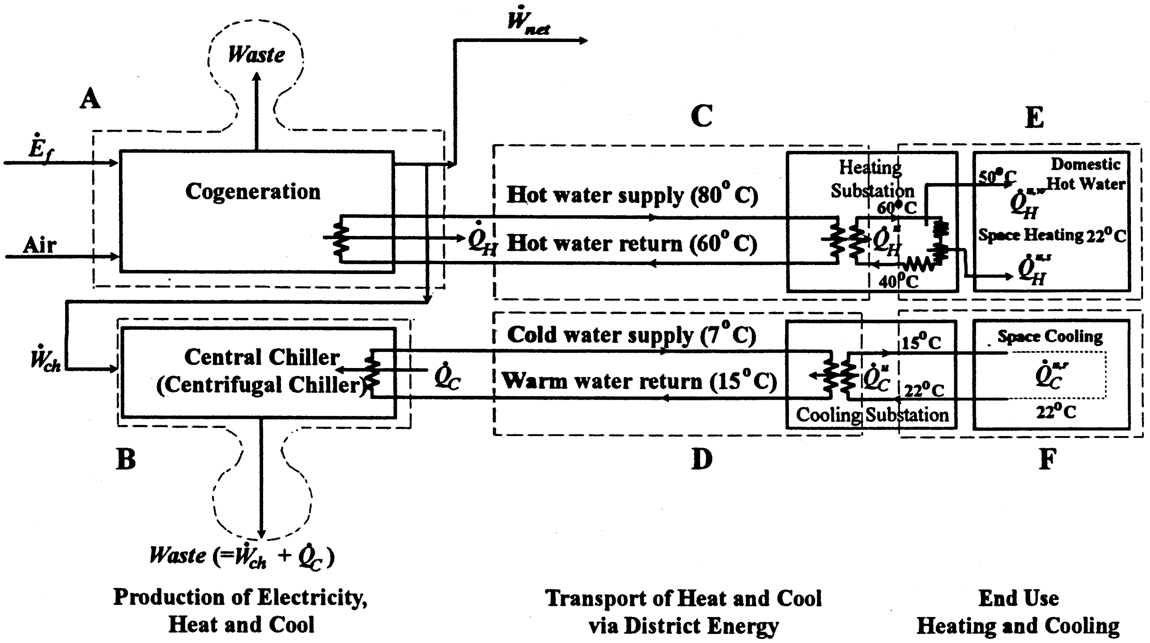

Figure 1. Simplified diagram of the cogeneration-based district energy system proposed by Edmonton Power. The system, which uses electric chillers, is divided into six subsections within three categories. On the left are production processes, including cogeneration of electricity and heat (A) and chilling (B). In the middle are district-energy transport processes, including district heating (C) and district cooling (D). On the right are end-user processes, including user heating (E) and user cooling (F).

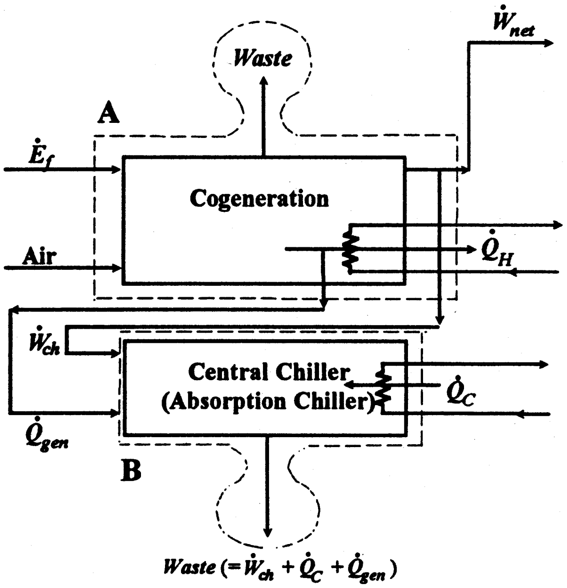

Figure 2. Modified version of production processes (units A and B) for the simplified diagram in Figure 1. In the modified system, the electric chillers are replaced with absorption chillers (single- or double-effect), driven mainly by heat from the cogeneration plant. The rest of the system in Figure 1 (units C to F) remains unchanged in the modified system. The temperature of the heating medium supplied to the absorption chillers is higher for the double-effect chiller relative to the single-effect machine.