

# **COMBINED COOLING, HEATING, AND POWER SYSTEMS**

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# COMBINED COOLING, HEATING, AND POWER SYSTEMS

## MODELING, OPTIMIZATION, AND OPERATION

**Yang Shi**

*University of Victoria, Canada*

**Mingxi Liu**

*University of Victoria, Canada*

**Fang Fang**

*North China Electric Power University, China*

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*To my beloved parents and family*  
–*Yang Shi*

*To my beloved parents and Jingwen*  
–*Mingxi Liu*

*To my beloved parents and family*  
–*Fang Fang*



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# Series Preface

The Wiley-ASME Press Series in Mechanical Engineering brings together two established leaders in mechanical engineering publishing to deliver high-quality, peer-reviewed books covering topics of current interest to engineers and researchers worldwide. The series publishes across the breadth of mechanical engineering, comprising research, design and development, and manufacturing. It includes monographs, references and course texts.

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# Preface

Combined cooling, heating and power (CCHP) is a feature of trigeneration systems able to supply cooling, heating, and electricity simultaneously. CCHP systems can be employed to provide buildings with cooling, heating, electricity, hot water and other uses of thermal energy. CCHP features with the great potential of dramatically increasing resource energy efficiency and reducing carbon dioxide emissions. Our intention through this book is to provide a timely account as well as an introductory exposure to the main developments in modeling, optimization, and operation of CCHP systems. At the time of conceiving this project, we believed that the development of a systematic framework on modeling and optimal operation design of CCHP systems was of paramount importance. A concise overview of the research area is presented in Chapter 1. We hope it will help readers arrive at a broader and more balanced view of CCHP systems. The remainder of the book presents the core contents, which are divided into five chapters. In Chapter 2, based on two conventional operation strategies, that is, following electric load (FEL) and following thermal load (FTL), a novel optimal switching operation strategy is presented. Chapter 3 presents a configuration with hybrid chillers and design of the optimal operation strategy. In Chapter 4, based on the concept of energy hub, a system matrix-based model is proposed to systematically facilitate the design of optimal operation strategies. Chapter 5 discusses the load prediction problem which plays an instrumental role in designing CCHP operation schemes. In Chapter 6, a complementary CCHP-organic Rankine cycle (CCHP-ORC) system is introduced.

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Yang Shi, Mingxi Liu, Fang Fang  
*Victoria, BC, Canada*

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# Acronyms

AFC	Alkaline Fuel Cell
ANN	Artificial Neural Network
AR	AutoRegressive
ARIMA	AutoRegressive Integrated Moving Average
ARMA	AutoRegressive Moving Average
ARMAX	AutoRegressive Moving Average with eXogenous inputs
ATC	Annual Total Cost
ATCS	Annual Total Cost Saving
ATD	Aggregate Thermal Demand
BFGS	Broyden–Fletcher–Goldfarb–Shanno
CCHP	Combined Cooling, Heating, and Power
CDE	Carbon Dioxide Emissions
CDER	Carbon Dioxide Emissions Reductions
CHP	Combined Heating and Power
CITHR	Cooling-side Incremental Trigeneration Heat Rate
COP	Coefficient of Performance
DHC	District Heating and Cooling
DOE	Department of Energy
EA	Evolutionary-Algorithmic
EBMUD	East Bay Municipal Utility District
EC	Evaluation Criteria
EDM	Electric Demand Management
EITHR	Electrical-side Incremental Trigeneration Heat Rate
EPA	Environmental Protection Agency
EUETS	European Union Emissions Trading Scheme
ec	Electric Chiller
FCL	Following Constant Load
FEL	Following the Electric Load
FTL	Following the Thermal Load
GA	Genetic Algorithm
GHG	GreenHouse Gas
GRG	Generalized Reduced Gradient
GRU	Gainesville Regional Utilities

HETL	Hybrid Electric-Thermal Load
hrc	Recovered Heat for Cooling
hrh	Recovered Heat for Heating
HRSG	Heat Recovery Steam Generator
hrs	Heat Recovery System
HTC	Hourly Total Cost
HTCS	Hourly Total Cost Savings
HVAC	Heating, Ventilation, and Air Conditioning
IC	Internal Combustion
IV	Instrument Variable
KKT	Karush–Kuhn–Tucker
LP	Linear Programming
LS	Least Squares
MA	Moving Average
MAE	Mean Absolute Error
MAFC	Magnesium-Air Fuel Cell
MAPE	Mean Absolute Percentage Error
MCFC	Molten Carbonate Fuel Cell
MILP	Mixed Integer Linear Programming
MINLP	Mixed Integer Non-Linear Programming
MSPE	Mean Square Prediction Error
MPC	Model Predictive Control
OLS	Ordinary Least Squares
ORC	Organic Rankine Cycle
PAFC	Phosphoric Acid Fuel Cell
PEMFC	Proton Exchange Membrane Fuel Cell
PEC	Primary Energy Consumption
PES	Primary Energy Savings
PGU	Power Generation Unit
PURPA	Public Utility Regulatory Policy Act
PV	PhotoVoltaic
QP	Quadratic Programming
SNPV	System Net Present Value
SOFC	Solid Oxide Fuel Cell
SP	Separation Production
SQP	Sequential Quadratic Programming
TDM	Thermal Demand Management
TITHR	Thermal-side Incremental Trigeneration Heat Rate
TPES	Trigeneration Primary Energy Saving
TRR	Total Revenue Requirement
TSLs	Two-Stage Least Squares
TSRLS	Two-Stage Recursive Least Squares
WADE	World Alliance for Decentralized Energy

# Symbols

$a_i(\star)$	The $i$ th equality constraint of variable $\star$
$ATC$	Annual total cost
$ATCS$	Annual total cost savings
$C_{ac}$	Unit price of the absorption chiller
$C_b$	Unit price of the boiler
$C_{ca}$	Carbon tax rate
$C_e$	Electricity rate
$C_{ec}$	Unit price of the electric chiller
$C_f$	Natural gas rate
$C_h$	Unit price of the heating unit
$c_j(\star)$	The $j$ th inequality constraint of variable $\star$
$C_{pgu}$	Unit price of the PGU
$C_s$	Electricity sold-back rates
$CDE$	Carbon dioxide emissions
$CDE^{CCHP}$	Carbon dioxide emissions of the CCHP system
$CDE_{FEL}^{CCHP}$	Carbon dioxide emissions of the CCHP system under FEL
$CDE_{FTL}^{CCHP}$	Carbon dioxide emissions of the CCHP system under FTL
$CDE^{SP}$	Carbon dioxide emissions of the SP system
$CDER$	Carbon dioxide emissions reductions
$COP_{ac}$	Coefficient of performance of the absorption chiller
$COP_{ec}$	Coefficient of performance of the electric chiller
$COST$	Operational cost
$COST_{FEL}^{CCHP}$	Operational cost of the CCHP system under FEL
$COST_{FTL}^{CCHP}$	Operational cost of the CCHP system under FTL
$COST^{SP}$	Operational cost of the SP system
$Cov[\bullet, \star]$	Covariance of variables $\bullet$ and $\star$

$E[\star]$	Expectation of variable $\star$
$E_{ec}$	Electricity consumed by the electric chiller in the CCHP system
$E_{ec}^{SP}$	Electricity consumed by the electric chiller in the SP system
$E_{excess}$	Excess electricity
$E_{grid}$	Purchased electricity from the grid by the CCHP system
$\check{E}_{grid}(t)$	Purchased electricity for compensating for the cooling gap
$E_{grid}^{SP}$	Purchased electricity from the grid by the SP system
$e_i$	Standard basis vector with the $i$ th element being 1
$E_i^\ell$	Electricity input of component $\ell$
$E_o^\ell$	Electricity output of component $\ell$
$\bar{E}_o^{pgu}$	Maximum electricity generated by the PGU
$E_{orc}$	Electricity output of the ORC
$E_p$	Parasitic electricity
$E_{pgu}$	Electricity generated from the PGU
$\bar{E}_{pgu}$	Maximum electricity generated by the PGU
$E_{pgu-FEL}$	Electricity generated from the PGU under FEL
$E_{pgu-FTL}$	Electricity generated from the PGU under FTL
$E_{pro}$	Electricity generated by the PGU
$E_{req}$	Electricity required by building users and the electric chiller
$E_{user}$	Electricity required by building users
$E_{userl}$	Lower bound of electricity required by building users
$E_{useru}$	Upper bound of electricity required by building users
$EC$	Evaluation criteria function value
$EC_{annual}$	Annual evaluation criteria function value
$EC_{FEL}$	Evaluation criteria function value of the CCHP system under FEL
$EC_{FTL}$	Evaluation criteria function value of the CCHP system under FTL
$EC_{hour}$	Hourly evaluation criteria function value
$EC_{hour,ij}$	Hourly evaluation criteria function value of day $i$ , hour $j$
$F_b$	Fuel consumed by the boiler in the CCHP system
$F_b^{SP}$	Fuel consumed by the boiler in the SP system
$F_{b-FEL}$	Fuel consumed by the boiler in the CCHP system under FEL
$F_{b-FTL}$	Fuel consumed by the boiler in the CCHP system under FTL
$F^{CCHP}$	Fuel consumed by the CCHP system
$F_i^\ell$	Fuel input of component $\ell$
$F_m$	Total fuel consumption
$\check{F}_m$	Additionally purchased fuel

$F_{m-FEL}$	Total fuel consumption of the CCHP system under FEL
$F_{m-FTL}$	Total fuel consumption of the CCHP system under FTL
$F_o^\ell$	Fuel output of component $\ell$
$F_{pgu}$	Fuel consumed by the PGU
$F_{pgu-FEL}$	Fuel consumed by the PGU in the CCHP system under FEL
$F_{pgu-FTL}$	Fuel consumed by the PGU in the CCHP system under FTL
$F_{pgum}$	Maximum fuel consumption of the PGU
$F_{pgumopt}$	Optimal PGU capacity
$F_{red}$	Reduced fuel consumption
$F^{SP}$	Fuel consumed by the SP system
$H^\ell$	Energy conversion matrix of component $\ell$
$h_1$	Enthalpy of organic fluid at the inlet of pump
$h_2$	Enthalpy of organic fluid at the outlet of pump
$h_{2s}$	Enthalpy at the outlet of pump for the isentropic case
$h_3$	Enthalpy of organic fluid at the outlet of the evaporator
$h_4$	Enthalpy of organic fluid at the outlet of the pump
$h_{4s}$	Enthalpy of organic fluid at the outlet of the turbine for the isentropic case
$HTC$	Hourly total cost
$HTC^{CCHP}$	Hourly total cost of the CCHP system
$HTC^{SP}$	Hourly total cost of the SP system
$HTCS$	Hourly total cost savings
$K$	Power to heat ratio
$k_e$	Site-to-primary energy conversion factor for electricity
$k_f$	Site-to-primary energy conversion factor for natural gas
$L$	Facility's life
$\max f(\bullet)$	Maximize the function value of $f(\bullet)$
$\min f(\bullet)$	Minimize the function value of $f(\bullet)$
$\max \{\bullet, \star\}$	Maximum value between $\bullet$ and $\star$
$\min \{\bullet, \star\}$	Minimum value between $\bullet$ and $\star$
$m_{orc}$	Organic fluid mass flow rate
$PEC$	Primary energy consumption
$PEC^{CCHP}$	Primary energy consumption of the CCHP system
$PEC_{FEL}^{CCHP}$	Primary energy consumption of the CCHP system under FEL
$PEC_{FTL}^{CCHP}$	Primary energy consumption of the CCHP system under FTL
$PEC^{SP}$	Primary energy consumption of the SP system

$PES$	Primary energy savings
$Q_{ac}$	Cooling energy provided by the absorption chiller
$Q_c$	Total cooling demand
$Q_{cd}$	Heat exchange of the condenser
$Q_{ec}$	Cooling energy provided by the electric chiller
$Q_{ep}$	Obtained heat by evaporator
$Q_{eq}$	Equivalent total thermal requirement at the output of the heat recovery system
$Q_b$	Thermal energy provided by the boiler in the CCHP system
$Q_b^{SP}$	Thermal energy provided by the boiler in the SP system
$Q_{gap}$	Thermal energy gap
$Q_h$	Total heating demand
$Q_{hi}^\ell$	Heating input of component $\ell$
$Q_{ho}^\ell$	Heating output of component $\ell$
$Q_{hrc}$	Thermal energy from the heat recovery system for the use of cooling
$Q_{hrh}$	Thermal energy from the heat recovery system for the use of heating
$Q_{pro}$	Thermal energy provided by the PGU
$Q_r$	Thermal energy provided by the heat recovery system
$Q_{req}$	Thermal energy required by building users and the electric chiller
$Q_{r-FEL}$	Thermal energy provided by the heat recovery system under FEL
$Q_{r-FTL}$	Thermal energy provided by the heat recovery system under FTL
$Q_{ro}$	Thermal input of the ORC
$Q_{user}$	Total thermal demand by building users
$R$	Capital recovery factor
$T_{dew}$	Dew-point temperature
$T_{dew}^o$	Observation of the dew-point temperature
$T_{dry}$	Dry-bulb temperature
$T_{dry}^o$	Observation of the dry-bulb temperature
$\hat{T}_{dry}$	Estimation of the dry-bulb temperature
$\mathcal{V}_i^\ell$	Energy input vector of component $\ell$
$\mathcal{V}_o^\ell$	Energy output vector of component $\ell$
$\hat{\mathcal{Y}}_o$	Forecasted load vector
$\bar{\mathcal{Y}}_o^\ell$	Upper bound of the output of component $\ell$
$\underline{\mathcal{Y}}_o^\ell$	Lower bound of the output of component $\ell$
$\text{Var}[\star]$	Variance of variable $\star$
$W_p$	Pump power

$x$	Electric cooling to cool load ratio
$y_c$	Variable of cooling load
$\hat{y}_c$	Variable of forecasted cooling load
$\tilde{y}_c$	Variable of remained cooling to be provided
$y_e$	Variable of electric load
$\hat{y}_e$	Variable of forecasted electric load
$y_h$	Variable of heating load
$\hat{y}_h$	Variable of forecasted heating load
$\tilde{y}_h$	Variable of remained heating to be provided
$z^{-\star}$	$\star$ time lags from the current time instant
$\Gamma_\ell$	Dispatch matrix of component $\ell$
$\eta_h$	Efficiency of the heating unit
$\eta_{pgu}$	Efficiency of the PGU
$\eta_{hrs}$	Efficiency of the heat recovery system
$\eta_b$	Efficiency of the boiler
$\eta_e^{SP}$	Generation efficiency of the SP system
$\eta_{grid}$	Transmission efficiency of local grid
$\eta_p$	Isentropic efficiency
$\eta_{orc}$	Efficiency of the ORC
$\eta_{gen}$	Efficiency of the electric generator
$\mu_e$	Carbon dioxide emissions conversion factor of electricity
$\mu_f$	Carbon dioxide emissions conversion factor of natural gas
$\xi$	Evaporator effectiveness
$\omega_i$	Weighting coefficient of the $i$ th criterion
$\nabla$	Gradient
$^\circ\text{C}$	Centigrade
$\exists$	Exists
$\in$	In
$\triangleq$	Define
$\sum$	Sum
$\forall$	For all
s.t.	Subject to
$\top$	Matrix/vector transpose
$\mathbb{R}^n$	Real vector space of dimension $n$
$\mathbb{R}^{n \times m}$	Real matrix space of dimension $n \times m$
$\bullet^*$	The optimal value of variable $\bullet$
$O$	Complexity





# Introduction

Combined cooling, heating, and power (CCHP) systems are known as trigeneration systems. They are designed to supply cooling, heating, and electricity simultaneously. The CCHP system has become a hot topic for its high system efficiency, high economic efficiency, and low greenhouse gas (GHG) emissions in recent years. The efficiency of the CCHP system depends on the appropriate system configuration, operation strategy, and facility selection. Due to the inherent and inevitable energy waste of traditional operation strategies, high-efficiency operation strategies are urged. To achieve the highest system efficiency, facilities in the system should be appropriately sized to match with the corresponding operation strategy.

In Chapter 1, the state-of-the-art of CCHP research is surveyed. First, the development and working scheme of the CCHP system is presented. Some analyses of the advantages of this system and a brief introduction to the related components are then given. In the second part of Chapter 1, we elaborately introduce various types of prime movers and thermally activated facilities. Recent research progress on the management, control, system optimization, and facility selection is summarized in the third part. The development of the CCHP system in representative countries and the development barriers are also discussed in Chapter 1.

The operation strategy has a direct impact on the CCHP system performance. To improve the operational performance, in Chapter 2, based on two conventional operation strategies, that is, following electric load (FEL) and following thermal load (FTL), a novel optimal switching operation strategy is proposed. Using this strategy, the whole operating space of the CCHP system is divided into several regions by one to three border surfaces determined by energy requirements and the evaluation criteria (EC). Then the operating point of the CCHP system is located in a corresponding operating mode region to achieve improved EC. The EC simultaneously considers the primary energy consumption, the operational cost, and the carbon dioxide emissions. The proposed strategy can reflect and balance the influences of energy requirements, energy prices, and emissions effectively.

Most of the improved operation strategies in the literature are based on the “balance” plane, matching of the electric demands with the thermal demands. However, in more than 95% energy demand patterns, the demands cannot match with each other on this exact “balance” plane. To continuously use the “balance” concept, in Chapter 3, the system configuration is modified from the one with a single absorption chiller

to be the one with hybrid chillers, thus expanding the “balance” plane to a “balance” space by tuning the electric cooling to cool load ratio. With this new “balance” space, an operation strategy is designed and the power generation unit (PGU) capacity is optimized according to the proposed operation strategy to reduce the energy waste and improve the system efficiency. A case study is conducted to verify the feasibility and effectiveness of the proposed operation strategy.

In Chapter 4, a more mathematical approach to scheduling the energy input and power flow is proposed. By using the concept of *energy hub*, the CCHP system is modeled in a matrix form. As a result, the whole CCHP system is an input–output model. Setting the objective function to be a weighted summation of primary energy savings (PES), hourly total cost savings (HTC), and carbon dioxide emissions reductions (CDER), the optimization problem, constrained by equality and inequality constraints, is solved to obtain the optimal operation strategy. The PGU capacity is also sized under the proposed optimal operation strategy. In the case study, compared with FEL and FTL, the proposed optimal operation strategy saves more primary energy and annual total cost, and can be more environmentally friendly.

Most of the current operation strategies are designed by assuming that accurate loads during the next time interval are already known. In Chapter 5, in order to solve the problem of unknown loads in practical applications, by using an Autoregressive Moving Average with exogenous inputs (ARMAX) model, whose parameters are identified by a proposed Ordinary Least Squares–Two-Stage Recursive Least Squares (OLS-TSRLS) algorithm, cooling, heating, and electrical loads in the future time intervals are forecasted. The identification procedure uses the dew-point temperature as the instrumental variable (IV) for the exogenous variable (dry-bulb temperature) to better explain the relation between exogenous and endogenous variables. TSRLS at the second stage helps to reduce the time complexity. A post-strategy is also proposed to compensate for the inaccurate forecasting. A case study is conducted to verify the feasibility and effectiveness of the proposed methods.

The electricity to thermal energy output ratio is an important impact factor for the operation strategy and performance of CCHP systems. If the energy requirements of users are managed to just match this ratio, the system efficiency would reach the maximum. However, due to the randomness of users’ demand, this situation is rarely achieved in practice. To solve this problem, a complementary CCHP-organic Rankine cycle (CCHP-ORC) system is configured in Chapter 6. The salient feature of this system is that its electricity to thermal energy output ratio can be adjusted by changing the loads of the electric chiller and the ORC dynamically. For such a system, an optimal operation strategy and a corresponding implemented decision-making process are presented within a wide load range. Case studies are conducted to verify the efficacy of the developed CCHP-ORC system.