Energy Conversion and Management 120 (2016) 157–196

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Review

Review of tri-generation technologies: Design evaluation, optimization, decision-making, and selection approach

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ARTICLE INFO

Article history:
Received 3 October 2015
Received in revised form 29 March 2016
Accepted 24 April 2016

Keywords:
Tri-generation
Prime mover
Heat recovery
Thermal storage
Evaluation criteria

ABSTRACT

Electricity, heating, and cooling are the three main components constituting the tripod of energy consumption in residential, commercial, and public buildings all around the world. Their separate generation causes higher fuel consumption, at a time where energy demands and fuel costs are continuously rising. Combined cooling, heating, and power (CCHP) or trigeneration could be a solution for such challenge yielding an efficient, reliable, flexible, competitive, and less pollutant alternative. A variety of trigeneration technologies are available and their proper choice is influenced by the employed energy system conditions and preferences. In this paper, different types of trigeneration systems are classified according to the prime mover, size and energy sequence usage. A leveled selection procedure is subsequently listed in the consecutive sections. The first level contains the applied prime mover technologies which are considered to be the heart of any CCHP system. The second level comprises the heat recovery equipment (heating and cooling) of which suitable selection should be compatible with the used prime mover. The third level includes the thermal energy storage system and heat transfer fluid to be employed. For each section of the paper, a survey of conducted studies with CHP/CCHP implementation is presented. A comprehensive table of evaluation criteria for such systems based on energy, exergy, economy, and environment measures is performed, along with a survey of the methods used in their design, optimization, and decision-making. Moreover, a classification diagram of the main CHP/CCHP system components is summarized. A general selection approach of the appropriate CCHP system according to specific needs is finally suggested. In almost all reviewed works, CCHP systems are found to have positive technical and performance impacts.

Contents

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http://dx.doi.org/10.1016/j.enconman.2016.04.085
0196-8904/

Nomenclature

A	surface area
AbC	absorption chiller
AdC	adsorption chiller
AFC	alkaline fuel cell
C	cost
CAPEX	capital expenditure
CC	capital cost
CCGT	combined cycle gas turbine
CCHP	combined cooling, heating, and power
CCP	combined cooling and power
CHP	combined heating and power
CHS	chemical heat storage
CI	compression ignition
Com	commercial
Con	condenser
COP	coefficient of performance
DHW	domestic hot water
DD	desiccant dehumidifier
EPC	exergetic production cost
ES	emissions savings
EUF	energy utilization factor
Eva	evaporator
FCS	fuel consumption/cost savings
FESR	fuel energy saving ratio
FUE	fuel utilization efficiency
FWT	feed water temperature
G	gega
GHG	greenhouse gas
GT	gas turbine
GWP	global warming potential
h	height
HHV	higher heating value
HP	high pressure
HRSG	heat recovery steam generator
HST	heat storage tank
HTF	heat transfer fluid
HX	heat exchanger
IC	internal combustion
ICE	internal combustion engine
Ind	industrial
IRR	internal return rate
L	length
LHS	latent heat storage
LHV	lower heating value
LNG	liquefied natural gas
LPG	liquefied petroleum gas
$\dot{m}$	flow rate
mg	mass
M	million/mega
MCFC	molten carbonate fuel cell
MP	middle pressure
MSCM	metric standard cubic meters
MT	micro-turbine
NG	natural gas
NPV	net present value
OCS	operating cost savings
ODP	ozone depletion potential
OPEX	operational expenditure
ORC	organic Rankine cycle
P	electric power
PAFC	phosphoric acid fuel cell
PBP	pay back period
PCM	phase change material
PEC	primary energy costs
PEMFC	proton exchange membrane fuel cell
PER	primary energy rate
PES	primary energy savings
PFI	performance fraction indicator
PHR	power to heat ratio
PHX	plate heat exchanger
PM	prime mover
ppb, ppm, ppmv	parts per billion, million, by volume
PPT	pinch point temperature
Pr	pressure
PVT	photovoltaic-thermal
Q	thermal power
Rec	recuperator
Reg	regenerator
Res	residential
RICE	reciprocating internal combustion engine
rpm	rotations per minute
S&THX	shell and tube heat exchanger
SE	stirling engine
SCP	specific cooling power
SHS	sensible heat storage
SOFC	solid oxide fuel cell
SS	stainless steel
ST	steam turbine
T	temperature
TES	thermal energy storage
U	overall heat transfer coefficient
U_f	fuel utilization factor
V	volume
w	width
WHRB	waste heat recovery boiler

Greek letters

h	energy efficiency
ε	exergy efficiency
ϕ	diameter
Δ	difference
w	rotational speed
m	micro

Subscripts

a	ambient
b	boiler
c	cooling
chw	chilled water
cw	cold water
e	electrical
eq	equivalent
eqm	equipment
ex	exhaust
f	fuel
h	heating
hw	hot water
Inv	Investment
in	input
max	maximum
min	minimum
o	overall
op	operating
opt	optimum
out	output
pgu	power generation unit
r	recovery