AIN SHAMS UNIVERSITY

FACULTY OF ENGINEERING

Mechanical Power Engineering

Thermo-economic driven planning of resource-efficient district combined cooling and power

A Thesis submitted in partial fulfillment of the requirements of the degree of

Master of Science in Mechanical Engineering

(Mechanical Power Engineering)

by

Mohamed Atef Mohamed Kamel Ahmed

Bachelor of Science in Mechanical Engineering

(Mechanical Power Engineering)

Faculty of Engineering, Ain Shams University, 2016

Supervised By

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Cairo - (2019)

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Statement

This thesis is submitted as a partial fulfillment of Master of Science in Mechanical Engineering Engineering, Faculty of Engineering, Ain shams University.

The author carried out the work included in this thesis, and no part of it has been submitted for a degree or a qualification at any other scientific entity.

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Abstract

Trigeneration energy systems have gathered considerable attention from energy specialists and energy economists. When adequately designed, trigeneration systems reduce the overall cost of energy production and lower the carbon footprint for every energy unit generated. However, their implementation in the buildings' industry faced many obstacles such as the inefficient sizing of their capacities, and their sub-optimal operational scheduling, which have led to high investment and operational costs compared to conventional systems.

Accordingly, an optimization tool has been modeled to find optimal planning, sizing and scheduling of trigeneration systems. The tool is used in decision-making process in all project phases. This is done by applying the energy hub concept under the constraints of maximizing a formulated combined efficiency that contains annualized total cost saving ratio (ATCSR), exergy efficiency (EXEff), fuel saving ratio (FSR) and carbon dioxide reduction ratio (CO2RR) using a weighing factor method. This is made by comparing each indicator to a conventional system in GAMS. Moreover, economical parameters (net present value, internal rate of return and payback period) are used to guarantee proper decision-making process. Using part load effect and variable capital costs of components to simulate the real case, the tool provides optimal planning, sizing and scheduling of all trigeneration systems.

Three case studies have been adopted in this thesis as direct applications for the optimization tool. One of them has dealt with the quantification of error resulting from using simple (constant efficiency) and linearized models for simplicity instead of part load (variable efficiency) models which simulate the real case and to what extent this approximation is valid and whether it should be used in future studies or not. A novel contribution has been presented to compare between both models which the Root Mean Square Difference (RMSD). It depends on the deviations of the combined efficiency the economic parameters. Results assured the importance of using part load models in future studies to guarantee more accuracy as deviations of results between both models can't be neglected.

The second one has dealt with the intervention of solar energy components such as: solar thermal collectors (SCs) and photovoltaics (PVs) into optimized trigeneration system by comparing a solar energy optimized trigeneration system to an optimized trigeneration system with no solar energy utilization. This thesis provides a system-comparison methodology to compare such systems. This optimal system-comparison gives a complete picture on the real effect of adding any solar component to a trigeneration system because it gives the solar system the freedom for more intervention with the system resulting in more enhanced performance. Results assured the importance of comparing energy systems based on the system-comparison methodology. Moreover, they came up with the conclusion that reducing the capital costs of solar energy systems will facilitate their deployment in future energy systems as they already prove their ability to increase overall combined efficiency of energy systems by decreasing the fuel used and emission produced.

The third one has dealt with the concept of Hybrid photovoltaic/ thermal collectors (PV/Ts) technology after they have evolved as a translation to the typical idea of the trigeneration because they produce both heat and electricity simultaneously with the same area decreasing the footprint needed by side-by-side photovoltaics (PVs) and solar thermal collectors (SCs). A methodology of

real system-level comparison is presented in contrary to component-level comparisons that are available in the open literature. This methodology depends on comparing an optimized Solar-CCHP system with side-by-side PVs and SCs, against a PVT-CCHP with hybrid photovoltaic/thermal collectors (PV/Ts) instead under a constrained area. Results came up with the conclusion that using PV/Ts instead of side-by-side PVs and SCs will yield higher combined efficiency but with lower Net Present Value (NPV) at normal price mode but with increasing the selling prices of sold electricity, PV/Ts are favorable due to higher combined efficiency and Net Present Value (NPV).

Keywords

Difference
Part load
Simple model
Trigeneration
Multi-objective
Optimization
Energy hub
Photovoltaics
Solar Thermal collectors
CCHP
Solar-CCHP
Comparison
Optimization
Hybrid photovoltaic/thermal collectors
Exergy
Key Performance Indicators (KPIs)

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I hope this work would help in developing the world and be a good reference for energy specialists.

List of Abbreviations

AC	absorption chiller
ATCSR	annualized total cost saving ratio
Cap	capital cost, $
CCHP	combined cooling, heating and power
CHP	combined heating and power
cload(t)	cooling load at time t, kW
CO2RR	carbon dioxide reduction ratio
COP	coefficient of performance
CRF	capital recovery factor
EC	vapor compression chiller
ecost	cost of producing CCHP-electricity, $/Kw
eload(t)	electrical load at time t, kW
ESF	electrical solar fraction
ESP	CCHP-electricity selling price, $/kW
EXEff	exergetic efficiency
FHL	following hybrid load operating strategy
FSR	fuel saving ratio
GAMS	general algebraic modeling system
GB	gas boiler
H	heat provided by the collector, kW
hload(t)	heating load at time t, kW
HRSG	heat recovery steam generator
ICE	Internal Combustion engine
IRR	internal rate of return
KPI	key performance indicator
LHV	lower heating value of natural gas (kWh/m^3)
LP	linear programming
MILP	mixed integer linear programming
MINLP	mixed integer nonlinear programming
NCF	net cash flow, $
NLP	non-linear programming
NOCT	nominal operating cell temperature
NPV	net present value, $
PBP	payback period, years
PV	photovoltaics
PVT-CCHP	trigeneration system with PV/Ts
Rev	annual revenues, $
RMINLP	relaxed mixed integer nonlinear programming
SC	solar collectors
scost	cost of producing Solar-electricity, $/kW
Solar-CCHP	trigeneration system with PVs and SCs
SSP	solar-electricity selling price, $/kW
TOU	time of use
TSF	thermal solar fraction

Subscripts

ac	absorption chiller
ACin	input heat to AC, kWh
ACN	rated capacity of absorption chiller, kW
amb	ambient temperature, K
cell	cell temperature, K
ec	vapor compression chiller
ECN	rated capacity of vapor compression chiller , kW
gb	gas boiler
GBN	rated capacity of gas boiler, kW
grid	grid parameters
he	heat exchanger
HEN	rated capacity of heat exchanger, kW
hr	heat recovered from HRSG, kWh
HRN	rated capacity of HRSG, kW
ice	internal combustion engine
ICEN	rated capacity of ICE, kW
in	entering the system
inv	investment cost, $
inverter	inverter
main	maintenance cost, $
mean	mean temperature, K
NG	natural gas
op	operation cost, $
out	leaving the system
pur	purchased from grid
pv	PV panels
PVN	rated PV efficiency
pvt	PVT-CCHP system variables
PVTN	rated PV/T efficiency
ref	reference system
relative	relative reference to conventional generation
sc	solar collectors
SCN	rated SC efficiency
solar	Solar-CCHP system variables
sold	sold to grid
sun	sun temperature
system	system parameters
total	sum of grid and system emissions in CCHP system
$total_{ref}$	sum of grid and system emissions in reference system

List of Symbols

b	binary variable for component selection at time t
d	deviation
F	fuel energy, kWh
Fdeviation	scheduling deviation, %
G	incident radiation, W/m^2
H	heat provided by the collector, kW
K	fitting constant
k	k-factor
M	maintenance cost, $/kWh
N	number
P	power produced or consumed, kW
Q	heat flow, kW
S	sold power to grid, kW
v	fuel flow rate, m^3/s
x	binary variable for component selection

Greek letters

η	efficiency
β	temperature coefficient, %/°C

Subscripts

c	cold water/cooling
e	electrical
h	hot water
n	annual at year n
t	thermal

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Publications

This thesis is based on the following papers:

1- Mohamed A. Kamel, Amr Y. Elbanhawy, Mahmoud Abo El-Nasr " A novel methodology to compare optimized CCHP and Solar-CCHP systems based on overall system-comparison". 2019 MIT Applied Energy "A+B" Symposium held in Boston, USA on 22nd to 24th May 2019.

2- Mohamed A. Kamel, Amr Y. Elbanhawy, Mahmoud Abo El-Nasr " Optimal planning, sizing and scheduling of trigeneration systems". Architecture and urbanism a smart look. The 3rd international conference of Architecture and Urban planning, Faculty of Engineering, Ain Shams University, 14-16 October 2019.

3- Mohamed A. Kamel, Amr Y. Elbanhawy, Mahmoud Abo El-Nasr " Quantification of error resulting from using simple model instead of part load model in optimal planning, sizing, scheduling and sensitivity analysis of trigeneration systems". Submitted for review in Applied Energy Elsevier Journal.

4- Mohamed A. Kamel, Amr Y. Elbanhawy, Mahmoud Abo El-Nasr " A novel methodology to compare on a system-basis between side-by-side photovoltaics and thermal collectors CCHP system and hybrid photovoltaic thermal collectors CCHP system". Submitted for review in Energy Conversion and Management Elsevier Journal.

Thesis outline

Chapter 1 states the motivation, objective, method, and scope of the work.
Chapter 2 provides State of the art on modeling and optimization of trigeneration energy systems.
Chapter 3 presents the methodology of the modeling and optimization of the adopted case studies.
Chapter 4 describes the case studies and the input data.
Chapter 5 presents the results and discussions of all case studies with sensitivity analyses.
Chapter 6 presents the results and discussions of sensitivity analyses.
Chapter 7 summarizes the thesis' novel contributions.
Chapter 8 points out the concluding remarks based on the results, recommendations and future work from author's point of view.