

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)

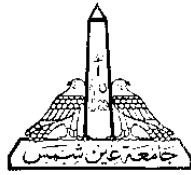
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Statement

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	<i>Subscripts</i>	
ATCSR	annualized total cost saving ratio	<i>ac</i>	absorption chiller
Cap	capital cost, \$	<i>ACin</i>	input heat to AC, kWh
CCHP	combined cooling, heating and power	<i>ACN</i>	rated capacity of absorption chiller,
CHP	combined heating and power	kW	
cload(t)	cooling load at time t, kW	<i>amb</i>	ambient temperature, K
CO2RR	carbon dioxide reduction ratio	<i>cell</i>	cell temperature, K
COP	coefficient of performance	<i>ec</i>	vapor compression chiller
CRF	capital recovery factor	<i>ECN</i>	rated capacity of vapor compression
EC	vapor compression chiller		chiller , kW
ecost	cost of producing CCHP-electricity,	<i>gb</i>	gas boiler
	\$/Kw	<i>GBN</i>	rated capacity of gas boiler, kW
eload(t)	electrical load at time t, kW	<i>grid</i>	grid parameters
ESF	electrical solar fraction	<i>he</i>	heat exchanger
ESP	CCHP-electricity selling price, \$/kW	<i>HEN</i>	rated capacity of heat exchanger, kW
EXEff	exergetic efficiency	<i>hr</i>	heat recovered from HRSG, kWh
FHL	following hybrid load operating	<i>HRN</i>	rated capacity of HRSG, kW
	strategy	<i>ice</i>	internal combustion engine
FSR	fuel saving ratio	<i>ICEN</i>	rated capacity of ICE, kW
GAMS	general algebraic modeling system	<i>in</i>	entering the system
GB	gas boiler	<i>inv</i>	investment cost, \$
H	heat provided by the collector, kW	<i>inverter</i>	inverter
hload(t)	heating load at time t, kW	<i>main</i>	maintenance cost, \$
HRSG	heat recovery steam generator	<i>mean</i>	mean temperature, K
ICE	Internal Combustion engine	<i>NG</i>	natural gas
IRR	internal rate of return	<i>op</i>	operation cost, \$
KPI	key performance indicator	<i>out</i>	leaving the system
LHV	lower heating value of natural gas	<i>pur</i>	purchased from grid
(kWh/m ³)		<i>pv</i>	PV panels
LP	linear programming	<i>PVN</i>	rated PV efficiency
MILP	mixed integer linear programming	<i>pvt</i>	PVT-CCHP system variables
MINLP	mixed integer nonlinear	<i>PVTN</i>	rated PV/T efficiency
	programming	<i>ref</i>	reference system
NCF	net cash flow, \$	<i>relative</i>	relative reference to conventional
NLP	non-linear programming	generation	
NOCT	nominal operating cell temperature	<i>sc</i>	solar collectors
NPV	net present value, \$	<i>SCN</i>	rated SC efficiency
PBP	payback period, years	<i>solar</i>	Solar-CCHP system variables
PV	photovoltaics	<i>sold</i>	sold to grid
PVT-CCHP	trigeneration system with PV/Ts	<i>sun</i>	sun temperature
Rev	annual revenues, \$	<i>system</i>	system parameters
RMINLP	relaxed mixed integer nonlinear	<i>total</i>	sum of grid and system emissions in
	programming		CCHP system
SC	solar collectors	<i>total_{ref}</i>	sum of grid and system emissions in
scost	cost of producing Solar-electricity,		reference system
	\$/kW		
Solar-CCHP	trigeneration system with PVs and		
	SCs		
SSP	solar-electricity selling price, \$/kW		
TOU	time of use		
TSF	thermal solar fraction		

List of Symbols

b	binary variable for component selection at time t
d	deviation
F	fuel energy, kWh
F _{deviation}	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

<i>c</i>	cold water/cooling
<i>e</i>	electrical
<i>h</i>	hot water
<i>n</i>	annual at year n
<i>t</i>	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.