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Analysis and sizing of thermal energy storage in combined heating, cooling and power plants for buildings

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HIGHLIGHTS

- ▶ Novel method to estimate the contribution of thermal energy storage in CHCP plants.
- ▶ Simple and accurate analysis of contributions of thermal storage.
- ▶ Application to the assessment and optimal sizing of thermal storage in CHCP plants.
- ▶ Thermal storage increases efficiency, coverage and economic benefit.
- ▶ Thermal storage allows increasing efficient operation of the plant.

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ABSTRACT

Thermal energy storage (TES) can lead to significant energy savings and economic benefits in combined heating, cooling and power plants (CHCPs) for buildings in the tertiary sector. However, their complex interactions with the rest of the CHCP system make their adequate sizing difficult without using extensive and detailed simulations. The authors have developed a new method to evaluate the thermal contribution of TES based on simple procedures. Comparisons with detailed simulations for a range of situations confirm the ability of this method to predict the effect of TES on CHCP systems with good approximation, as well as to find the optimal size in a relatively simple manner and with few required data. The case studies show a strong dependence of the TES contribution on the demands profile and the operation strategy. However, adequately sized TES are proven to bring relevant energy savings as well as economic profit to CHCP plants. In this paper, sizing procedures are provided to find the optimal volume both in terms of thermodynamic efficiency and of economic profit.

1. Introduction

In order to reach a sustainable development in our society, it is crucial to improve energy efficiency as one of the most effective means to alleviate resources depletion, energy dependence and pollution. In this context, great efforts are being devoted to the integration of energy generation and consumption systems as one of the most promising options to increase energy savings from a global point of view. Considering the high potential for energy savings that exists in the tertiary and residential sectors (according to the European Energy Agency, over 50% [1]), the application of high efficiency co- and trigeneration schemes to HVAC in buildings could result in great improvements.

Although the combined production of heating, cooling and power (CHCP) could bring not only major environmental benefits but also considerable economic profits, its popularization is hindered by uncertainties derived from variability of the energy demand in these sectors, the consequent difficulty to couple operation and demands and its impact on economic results and risk [2]. Improved waste heat utilization could contribute to the economic feasibility of CHCP plants in the tertiary and residential sectors [3]. The use of heat storage systems in CHP and CHCP systems could help alleviating the negative effects of variability of energy demand by improving their coupling with energy generation profiles [4,5]. These devices help use better the residual heat, which in turn results in better efficiency, longer and easier operation, higher incomes from energy sale and lower economic risk [4–13,2,14–22].

Inadequate sizing of CHP facilities and thermal energy storage (TES) devices is frequent [4,6] and can lead to problems such as heat wasting, underuse of energy savings potential of the system or oversizing (with excessive cost and space use). Although evaluation approaches exist for the sizing of TES in boiler plants in industrial facilities [7], the authors have not found in the published literature simple methods to size TES to maximize benefits in CHCP

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Nomenclature

Abbreviations

ATD	aggregated thermal demand
CHCP	combined heating, cooling and power (trigeneration)
CHP	combined heating and power (cogeneration)
ESCO	energy Services Company
H	hotel
HSC	hotel and shopping center
SC	shopping center
TES	thermal energy storage

Parameters

cap	specific capacity of thermal storage device (kW h/m^3)
COP	coefficient of performance of the chiller (−)
OM	operation and maintenance specific costs (€/MW h)
p	price for energy sale or purchase (€/MW h)
Ref	reference for efficiency (%)
t	amortization period for investment (years)

Variables

D	energy demand (kW h)
E	generated or consumed energy (kW h)
ER	estimated economic returns (kW h)
Inc.	incomes (€)
inv	investment costs (€)
OP	operation period during a year (h)
P	electric output of engine (kW)
PES	primary energy savings = $1-1/(\eta_P/\mathrm{Ref}_P - \eta_V/\mathrm{Ref}_H)$ (%)
Q	thermal output of engine (kW)
R	frigorific output of absorption chiller (kW)
vol	volume of the TES device (m^3)

α	ratio between heat for cooling and total thermal energy (%)
β	ratio between covered and demanded energy (%)
η	efficiency (%)

Subscripts

d	daily
e	estimated with simplified calculation methods
h	hourly
H	thermal = heating + heat for cooling
F	fuel (energy, referred to LHV)
max	maximal
opt	optimal
P	electric
Q	heating
QR	heat for cooling
R	cooling
s	calculated with detailed simulation software
V	useful = heating + cooling
vol	corresponding to a full TES device of a given volume

Superscripts

$*$	corrected
0	derived from the system without TES
cov	covered (demand)
ncov	not covered (uncovered) demand
nrec	not recycled (unused) energy
rec	recycled (wasted) energy
TES	derived from the thermal energy storage

plants without needing extensive and comprehensive calculations. The effect of thermal storage on these systems is not linear [8] due to the complex interaction between demand profiles, operation of the prime movers and characteristics of the equipment, and the evaluation and optimal sizing of the devices is not trivial. It has been stated that TES size should be evaluated case by case [9] which explains that many previous works have relied on extensive parametric studies using specific simulation software in order to select optimal designs as those yielding the best results in the explored ranges [9–12]. Optimization algorithms have also been used for the global design of CHP systems with TES, based on mathematical programming using linear [13,2,14] or nonlinear [15–17] approaches or on heuristic methods using evolutionary algorithms [18,19]. Other approaches are based on simplistic rules that do not consider the case-specific interactions between demands, operation, TES and other equipment [20,21] and therefore are not able to find the optimal size in a particular application but just provide a rough assessment.

All these approaches may be used to evaluate the contribution of the thermal storage in energy plants but they seem to have notable drawbacks when a suitable sizing method for the TES device is sought. Thus, they are either very simple approaches that disregard important case-bound aspects, or too complex, because they need extensive calculations or complex algorithms based on comprehensive numerical simulations in order to reproduce the asynchronous dynamics of the storage device. This paper proposes a novel, alternative method, as simple as practical, to evaluate the contribution of TES to CHCP systems as a function of its capacity and to optimally size. It has been specially designed for residential and tertiary buildings, where the high variability (in time and among different cases) of thermal demands is probably the main challenge for analytical methods.

In a previous work [22], the authors presented methods for the thermal analysis (ATD$_e$ method) and optimal sizing (PES$_e$ strategy) of CHCP systems composed of an engine, heat exchangers and absorption chillers. The 'extended ATD$_e$ method' is a modification of the first one and it has been designed to evaluate the contribution of thermal storage to the thermal performance of the plant. This paper describes the calculation procedure and presents a critical analysis of its associated assumptions and procedures. The potential of the method has been addressed through its application to the thermodynamic and economic evaluation of three case studies. Finally, the use of the method for the optimal sizing of thermal storage devices in CHP and CHCP plants is treated in greater depth in the last section of the paper.

2. Objectives and constraints

2.1. Case studies

The potential for energy savings is especially important in the tertiary sector, where large amounts of energy are usually covered by conventional technologies. This study focuses on buildings of this sector, where an Energy Services Company (ESCO) would install and manage a CHCP system to sell the generated electricity to the grid at special prices and the recovered thermal energy to the building customers. The fraction of the demand that is not covered by the residual heat of the plant would be supplied by auxiliary devices owned by the building, therefore it is not considered in the present research.

Different types of buildings display widely different thermal demands, in terms of the relative magnitude of or their fluctuation patterns. Three examples of application are analyzed in this paper: