Energy Conversion and Management 149 (2017) 631–645

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Design optimization and sensitivity analysis of a biomass-fired combined cooling, heating and power system with thermal energy storage systems

Martina Caliano[a,*], Nicola Bianco[a], Giorgio Graditi[b], Luigi Mongibello[b]

[a] Dipartimento di Ingegneria Industriale (DII), Università di Napoli Federico II, Napoli, Italy
[b] ENEA, Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Portici Research Center, Portici (NA), Italy

ARTICLE INFO

Keywords:
Biomass
Combined Cooling, Heating and Power (CCHP) system
Feasible investment cost
Thermal energy storage
Sensitivity analysis
Cold thermal energy storage
Design optimization

ABSTRACT

In this work, an operation strategy for a biomass-fired combined cooling, heating and power system, composed of a cogeneration unit, an absorption chiller, and a thermal energy storage system, is formulated in order to satisfy time-varying energy demands of an Italian cluster of residential multi-apartment buildings. This operation strategy is adopted for performing the economical optimization of the design of two of the devices composing the combined cooling, heating and power system, namely the absorption chiller and the storage system. A sensitivity analysis is carried out in order to evaluate the impact of the incentive for the electricity generation on the optimized results, and also to evaluate, separately, the effects of the variation of the absorption chiller size, and the effects of the variation of the thermal energy storage system size on the system performance. In addition, the inclusion into the system of a cold thermal energy storage system is analyzed, as well, assuming different possible values for the cold storage system cost. The results of the sensitivity analysis indicate that the most influencing factors from the economical point of view are represented by the incentive for the electricity generation and the absorption chiller power. Results also show that the combined use of a thermal energy storage and of a cold thermal energy storage during the hot season could represent a viable solution from the economical point of view.

1. Introduction

Biomass, particularly wood, used for heating, cooling and electricity generation is one of the biggest source of renewable energy in the EU and is expected to have a key role in the achievement of the 20% EU renewable energy target by 2020. Moreover, a sustainable use of biomass can give a great contribution in addressing concerns about climate change and security of energy supply, also supporting economic growth and development [1]. In the residential sector, biomass is usually used to feed small-scale stoves. However, its use in Combined Heat and Power (CHP) plants is demonstrated to have substantial benefits with respect to biomass-fired systems providing separate generation of power and heat, and its expansion is further promoted by the EU energy efficiency directive [2].

In the last years, many authors have studied biomass-based polygeneration systems, conducting economic, energetic and exergetic analyses, also aimed at the evaluation of such systems performance with respect to systems for separate generation. Maraver et al. [3,4] presented a review on the technologies involved in biomass-fired Combined Cooling Heat and Power (CCHP) systems, also evaluating their performance in comparison to stand-alone conventional systems. Huang et al. [5] analyzed the technical and economic performances of a small-scale biomass-fuelled CCHP plant using an organic Rankine cycle to provide electricity and heat for building use. Harrod et al. [6] evaluated the cost and energy savings obtained by using a biomass-fired Stirling engine as a part of a CCHP system for building use. Calise et al. [7] simulated dynamically and investigated a polygeneration system where a reciprocating engine fed by vegetable oil was included. Pfeifer et al. [8] investigated the feasibility of CHP facilities fuelled by biomass in the Republic of Croatia, by considering several costs of biomass, and investment costs of the CHP systems. Gholamian et al. [9] performed a comprehensive thermodynamic modeling and environmental impact assessment for a CHP plant, composed of a wood biomass-fuelled gas turbine and a S-CO_2 cycle coupled with a domestic water heater. Borsukiewicz-Gozdur et al. [10] analyzed three variants of the same CHP plant based on organic Rankine cycle and fuelled with sawmill waste, in Poland. Amirante and Tamburrano [11] analyzed the use of small combined cycles for simultaneous generation of heat and power from the external combustion of solid biomass and low quality biofuels. Wang et al. [12] analyzed the performance of a biomass CCHP system

* Corresponding author.
E-mail address: martina.caliano@enea.it (M. Caliano).

http://dx.doi.org/10.1016/j.enconman.2017.07.048
Received 20 April 2017; Received in revised form 17 July 2017; Accepted 23 July 2017

Nomenclature

C	capacity (kWh)
E	energy (kWh)
ES	economic saving (€)
F	cash flow (€)
FIC	feasible investment cost (€)
FP	feed-in premium (€/MWh)
FT	feed-in tariff (€/MWh)
I	investment cost (€)
j	years
Lf	loss factor (%)
OEB	operational economic balance (€)
$O_{bj}F$	objective function
OM	operation and maintenance cost (€)
P	power (kW)
PES	Primary Energy Saving index
$UHEV$	useful heat economic value (€/kWh)
UHF	useful heat fraction

Symbols

η	efficiency

Subscripts

AB	auxiliary boilers
AC	absorption chiller
biom	referred to biomass
c	referred to cooling
CHP	combined heat and power
cost	cost (€/kWh)
CTES	cold energy storage system
DHW	domestic hot water
dumped	energy dumped
EC	electrical chillers
el	electric
LHV	lower heat value
max	maximum
sent	relative to the electricity released to the grid
surplus	thermal energy surplus
taken	relative to the electricity taken from the grid
TES	thermal energy storage
th	thermal
user	user

Superscripts

*	solution of the 2-variables optimization problem
″	relative to non-dimensional variables

Acronyms

AB	Auxiliary Boiler
AC	Absorption Chiller
AH	Ambient Heating
CCHP	Combined Cooling, Heat and Power
CHP	Combined Heat and Power
COP	Coefficient of Performance
CTES	Cold Thermal Energy Storage
DHW	Domestic Hot Water
DTL	Distribution Thermal Losses
EC	Electrical Chiller
RES	Renewable Energy Sources
TES	Thermal Energy Storage

in three different operating conditions: summer, winter, and the transitional seasons. In another work, Wang et al. [13] conducted cost allocation and sensitivity analysis of the CCHP system integrated with biomass gasification based on exergoeconomic methodology. Camporeale et al. [14] analyzed and compared, from the economic and energetic points of view, three operation strategies for a CHP plant fired by a mix of biomass and natural gas, to serve a residential demand. Bai et al. [15] analyzed the thermodynamic and economic performances of a polygeneration system based on the thermal gasification of cotton stalk by concentrated solar power. Li et al. [16] analyzed a cogeneration system coupling biomass partial gasification and ground source heat pump. Vakalis et al. [17] have recently introduced an integrated efficiency index that can be used to compare the thermodynamic performances of different polygeneration systems based on small-scale biomass gasifiers.

As many researches pointed out, optimization of polygeneration systems design and operational strategy is crucial to improve energy efficiency and to reduce overall energy costs and greenhouse gas emissions. Ahmadi et al. [18] analyzed and optimized a complex multigeneration system considering as objectives the total cost rate minimization and the exergy efficiency maximization. Shaneb et al. [19] proposed an online approach for the operation optimization of micro-CHP systems. Fuentes-Cortés et al. [20] minimized the cost and the environmental impact of two residential users in Mexico. Li et al. [21] optimized the design and the operation strategy of a CCHP system from the energetic, economic, and environmental viewpoints, for hotels, offices and residential buildings in Dalian (China). Mongibello et al. [22] and Caliano et al. [23] introduced a novel full-load heat-driven operation strategy for natural gas-fired CHP systems, evaluating economic and environmental benefits of such approach. In another work, Mongibello et al. [24] compared two different operation strategies for residential CHP systems, i.e. heat dumping and load partialization, by conducting an economic optimization and an environmental analysis. Franco et al. [25] defined an optimal operational strategy for CHP plants connected to civil/residential district heating networks, based on a multi-objective approach. Several studies on operation and design optimization of biomass-fuelled polygeneration systems have been published in the last years. Lund et al. [26] presented an optimal design methodology for small CHP plants in Danish market in which the plant size was optimized against various electricity prices. Taljan et al. [27] optimized economically the operation of a biomass CHP plant and the heat storage system. Noussan et al. [28] found out the optimal configuration of a biomass-fired CHP system with thermal energy storage from the economic and energetic points of view. Recently, many studies have been also focused on real-time management and dynamic optimization of smart polygeneration systems, taking into account the fluctuations occurring at the supply side and/or at the demand one, as the works of Powell et al. [29] and Rossi et al. [30]. Dominković et al. [31] developed an optimization model for combining biomass trigeneration energy system and pit thermal energy storage for the Croatian market.

This paper presents the operation strategy for biomass-fired CCHP systems formulated to satisfy the time-varying energy demands of an Italian cluster of residential multi-apartment buildings. The results of the design optimization of two devices composing the system, namely the absorption chiller and the thermal energy storage system, performed by implementing the developed operation strategy are shown and discussed. Furthermore, the impact of the incentive for the electricity generation on the optimized results is also analyzed. Finally, the optimized results obtained including a cold storage system into the