Applied Energy 124 (2014) 298–308

Contents lists available at ScienceDirect

Applied Energy

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

Optimization of a Distributed Cogeneration System with solar district heating

Dario Buoro [a], Piero Pinamonti [a], Mauro Reini [b,*]

[a] Electrical, Management and Mechanical Engineering Dept., University of Udine, via delle Scienze 208, 33100 Udine, Italy
[b] Engineering and Architecture Dept., University of Trieste, via Valerio 10, 34127 Trieste, Italy

HIGHLIGHTS

- Definition of a multi objective optimization model for a distributed renewable energy supply system.
- Distributed Cogeneration System integrated with central solar field and long term heat storage.
- Optimization of an industrial area energy system from environmental and economic points of view.
- Investigation of the electricity carbon intensity variation on the optimal system configuration.

ARTICLE INFO

Article history:
Received 2 January 2013
Received in revised form 19 February 2014
Accepted 24 February 2014
Available online 3 April 2014

Keywords:
Cogeneration
Distributed renewable system
Distributed energy system
Seasonal thermal storage
Solar field

ABSTRACT

The aim of the paper is to identify the optimal energy production system and its optimal operation strategy required to satisfy the energy demand of a set of users in an industrial area. A distributed energy supply system is made up of a district heating network, a solar thermal plant with long term heat storage, a set of Combined Heat and Power units and conventional components also, such as boilers and compression chillers. In this way the required heat can be produced by solar thermal modules, by natural gas cogenerators, or by conventional boilers. The decision variable set of the optimization procedure includes the sizes of various components, the solar field extension and the thermal energy recovered in the heat storage, while additional binary decision variables describe the existence/absence of each considered component and its on/off operation status.

The optimization algorithm is based on a Mixed Integer Linear Programming (MILP) model that minimizes the total annual cost for owning, maintaining and operating the whole energy supply system. It allows to calculate both the economic and the environmental benefits of the solar thermal plant, cooperating with the cogeneration units, as well as the share of the thermal demand covered by renewable energy, in the optimal solutions.

The results obtained analyzing different system configurations show that the minimum value of the average useful heat costs is achieved when cogenerators, district heating network, solar field and heat storage are all included in the energy supply system and optimized consistently. Thus, the integrated solution turns out to be the best from both the economic and environmental points of view.

1. Introduction

Distributed cogeneration and trigeneration systems integrated with renewable energy systems allow achieving economic and energy savings, both in residential and industrial sectors [1]. Especially considering a set of industrial users, characterized by quite constant and high energy consumptions all year long, the adoption of such smart a solution can lead to increase the whole energy efficiency of the system and thus to reduce costs, primary energy usage and polluting emissions. However, the expected performances could not be obtained without adopting the configuration and the operation strategy resulting from an optimization procedure of the whole system [2–9].

The problem concerning with the optimization of complex distributed energy supply systems, including also Combined Heat and Power (CHP) and Combined Cooling Heat and Power (CCHP) systems was dealt with by Sakawa et al. [10] and by Weber et al. [11], while other references are available dealing with the optimal

* Corresponding author. Tel.: +39 3497974427.
E-mail addresses: dario.buoro@uniud.it (D. Buoro), piero.pinamonti@uniud.it (P. Pinamonti), mauro.reini@units.it (M. Reini).

http://dx.doi.org/10.1016/j.apenergy.2014.02.062
0306-2619/© 2014 Published by Elsevier Ltd.

Nomenclature

η_{boi}	Boiler efficiency	ETC	Evacuated tubular collectors
ABS	Absorption chiller	F_g	Natural gas consumption (kWh)
ATES	Aquifer thermal energy storage	FPC	Flat plate collectors
BOI	Boiler	H_{dem}	Total thermal demand (kWh_{th}/y)
BTES	Bore hole thermal energy storage	i	Interest rate
CCHP	Combined Cooling Heat and Power System	ICE	Internal combustion engine
C_{dem}	Cooling demand	Inv	Total investment cost (€)
C_{el}	Annual cost of electricity purchased in the conventional situation (€/y)	IS	Isolated systems
c_{ep}	Purchase price of electricity (€/kWh_{el})	j	Technology
c_{es}	Sale price of electricity (€/kWh_{el})	k	User, coefficient
C_{fr}	Annual cost of cooling energy produced in the conventional situation (€/y)	MILP	Mixed Integer Linear Programming
c_{gas}	Purchase price of natural gas (€/kWh_{th})	MTG	Microgas turbine
$\overline{C_{heat}}$	Average heat cost (€/kWh_{th})	n	Life span
CHP	Combined Heat and Power System	Obj	Objective function (€/y)
C_{inv}	Annual investment cost (€/y)	PBP	Pay back period
C_{man}	Annual maintenance cost (€/y)	PES	Primary energy saving
COP	Coefficient of performance	PTES	Pit thermal energy storage
C_{ope}	Annual operating cost (€/y)	R_{dem}	Total cooling demand (kWh_{co}/y)
CS	Conventional system	REF	Mechanical chiller
DCS	Distributed Cogeneration System	rf	Capital recovery factor (y^{-1})
DHN	District heating network	R	Thermal loss coefficient
DRS	Distributed renewable system	SDH	Solar District Heating
E_{dem}	Total electrical demand (kWh_{el}/y)	STOR	Heat storage
E_p	Purchased electricity (kWh_{el})	t	Time interval
E_s	Sold electricity (kWh_{el})	TG	Gas turbine
		TTES	Tank thermal energy storage

design of district heating systems [12–15]. However, these optimization models generally consider residential users, rather than industrial ones as presented in this paper. In addition the solar thermal plant, possibly integrated with a long term storage, is generally taken into account as an alternative to CHP systems, so that the optimization deals only with one of the two solutions. An example of optimization models for industrial energy systems is proposed by Karlsson [16], a district heating networks is introduced by Chinese et al. [17], Lozano et al. [18] presents the thermoeconomic cost analysis of central solar heating plants, combined with a seasonal storage, while Barbieri et al. [19] analyze the inclunce of the thermal energy storage size for micro-CHP systems.

The current study presents the optimization of a distributed energy supply system, designed to satisfy the thermal, cooling and electrical demands of nine industrial facilities located in the northeast of Italy. The paper introduces the integration between conventional power sources and renewable energies in an industrial area, designing a solar district heating plant coupled with long term storage. This alternative is increasing in importance, as it is a valid solution to overcome the mismatch problem between the availability of the solar source and the energy user's demand in the residential sector [20–22].

The aim of the paper is to understand if the integrated solution is still valid for industrial utilities characterized by the heat demand less affected by seasonal variations all year long, by means of the optimization of the synthesis, design and operation of the whole system. The results of the optimizations have been used to identify the heat average costs associated with different plant configurations.

In the presented optimization the electrical energy, cold water and heat demands are known in advance and the layout and the size of the heating network is fixed. Notice that a model quite similar to the one presented in this paper can be used for optimizing DHN design too [23–27]. This paper differs from the previews ones as integrates renewable sources which was never considered in previews studies. All users can be connected to each other through the DHN, therefore the related production units may send heat to other users through the DHN as well as to the storage. Moreover, only the production units related to users requiring cooling energy can be equipped with absorption chillers driven by cogenerated heat. The solar thermal plant is also part of the superstructure and it produces thermal energy that can be sent either to the users or to the long term storage. Heat and electric power can be provided either by a large centralized CHP plant (internal combustion engine ICE) or by small-scale CHP systems (ICE or micro gas turbines MTG), properly located close to, or inside, the factories. Conventional boilers and vapor compression chillers can also be installed inside the factories or in the centralized plant, and each unit is connected to the electricity network. The optimal solution is a compromise that depends on many variables; therefore it is very difficult to find the best solution without solving an optimization problem.

In previous works of the authors, MILP models have been developed to optimize the design and operation of distributed CCHP systems in a tertiary sector scenario, considering different technologies and taking into account the effects of various economic support policies [23–26]. A similar model has been applied to an industrial area considering also the thermal inertia of the network in [28].

In this study, the integration between distributed energy supply system, solar thermal plant and heat storage is introduced, applying the model to an industrial scenario with the aim of determining which is the best configuration and operation in terms of both economic and environmental benefits, and how it is affected by the thermal storage heat losses.

The model used to solve the optimization problem is based on a MILP algorithm. The objective function takes into account the total annual cost for purchasing, maintaining and operating the whole distributed energy system. The optimization is subject to the constraints that express components operation characteristics, energy