Applied Energy 177 (2016) 553–569

Contents lists available at ScienceDirect

Applied Energy

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

Valuation under uncertain energy prices and load demands of micro-CHP plants supplemented by optimally switched thermal energy storage

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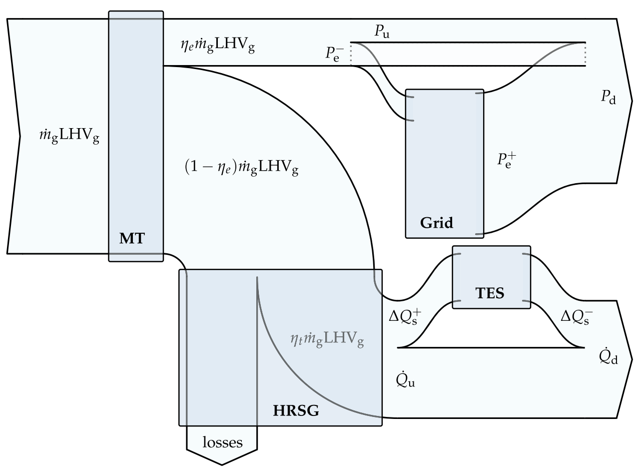
HIGHLIGHTS

- Cost improvements occur in a CHP plant supplemented by TES.
- An efficient dynamic program approach is detailed, based on Bellmans' principle.
- The program yields the optimal switching of the TES under uncertainty.
- The analysis elaborates on the uncertainty of prices and load demands.
- Optimality in component sizes ensues from optimal switching of the TES.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 22 January 2016
Received in revised form 14 April 2016
Accepted 14 May 2016

Keywords:
Combined heat and power (CHP)
Thermal energy storage (TES)
Optimization

ABSTRACT

This paper aims at providing insight on the ability that thermal energy storage (TES) systems have to reduce the cost of operating CHP plants, when an optimal switching policy is adopted to regulate the storage level under uncertain market conditions and also uncertain load demands.

To achieve this goal, this paper first proposes an efficient program to determine such an optimal policy, conceptually in line with the energy arbitrage capabilities attributed to electrical energy storage. The proposed algorithm is based on dynamic programming to cope with the stochastic nature of the problem in a Monte Carlo framework, while still keeping down its dimensionality. In addition, it is structured around simple manipulations of third-order tensors, which demonstrate to be effective in accelerating the speed of convergence.

The program has been thereafter applied to a case analysis, based on a gas microturbine (MT) powering a small-size CHP plant, with associated TES and peak boiler; with a detailed formulation of the efficiency deterioration of the system at part-load operation. The optimal switching policy ensuing from solving the problem by means of the proposed algorithm shows to be strongly dependent on the plant layout. Additionally, the efficiency deterioration, as well as the existence of operation thresholds because of

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http://dx.doi.org/10.1016/j.apenergy.2016.05.075

Nomenclature

$\mathcal{I}_m$	set of possible regimes	$\dot{Q}_d$	rate of heat demand (W)
L	number of storage levels	Q_n	TES nominal capacity (W h)
LHV_g	lower heating value of gas (W h/g)	ΔQ_s	change in the storage energy level (W h)
ℓ_t	level of storage at step t	P_e	electric power drawn from the grid (W)
$\dot{m}_g$	rate of gas consumption (g/s)	η_e	electrical efficiency
N	number of intervals over the optimization horizon	η_b	boiler efficiency
t	time step	λ	stochastic process reversion speed
u_t	control action at step t	μ	stochastic process level
X_t	generic state variable	π_g	gas price (€/MW h)
P_{CHP}	electrical power produced by the CHP system (W)	π_e	electricity price (€/MW h)
P_d	electrical power demand (W)	σ	stochastic process volatility
$\dot{Q}_b$	rate of heat production by the auxiliary boiler (W)	τ_0	first step of the optimization horizon
$\dot{Q}_{CHP}$	rate of heat production by the CHP system (W)	τ_N	final step of the optimization horizon

increased pollutant emissions, relevantly affect the optimal switching policy. An interpretation of the reasons why this occurs, along with a characterization, is provided based on the results yielded by the algorithm. Finally, a sensitivity analysis of the cost of operating the plant under different assumptions leads to a discussion about the optimal and threshold sizes of the MT and the TES.

1. Introduction

Cogeneration or combined heat and power (CHP) systems recover the heat rejected from power production to provide process, space, or water heating in industry and buildings. The rationale behind its use is that CHP effectively provides a cost reduction in supplying a heat load by recovering the excess heat coming from electricity generation; that otherwise would be rejected to the atmosphere. This immediately entails an increase in the overall plant efficiency and a decrease of greenhouse gas emissions, whereupon understandably CHP has gained clear acceptation in the power generation field. In fact, the proportion of total electric output generated by CHP activity, the necessary and sufficient indicator of CHP performance according to [1], reached 11.7% in EU-28 in 2013 [2]. Slovakia is the EU member with the highest proportion of CHP power production (77%), followed by Denmark (50.6%).

Energy storage provides a number of interesting functionalities based on delaying the use of energy obtained from power or heat sources. In the case of only electric power, Luo et al. cite twenty-five possible fields of application of electric energy storage in their comprehensive review [3]. In the case of only heat usage, a variety of application fields of thermal energy storage (TES) may be similarly inferred from [4], where also a detailed classification of TES is offered (see also [5]). In the case of CHP, where both heat and power are intrinsically coupled, the functionality of energy storage is to virtually decouple the supply of both types of energy, by regulating the delivery of heat or power from the generation plant to meet the uncoupled heat and power demands. Specifically in this paper, we have opted for the use of the TES, as a complement to a heat-driven CHP system. However, as it will be evident later, the application of the proposed algorithm to electric energy storage in a similar CHP context is straightforward, adding a functionality to the list in [3].

The incorporation of TES in the CHP system could influence decisions not only about new investments in CHP, but also about its operation and exploitation, as it can affect the cash-flows of a power plant during its lifetime. However, the final effect of TES on the power plant profitability is ambiguous, as it depends on the power and heat loads, the electricity and gas prices, the TES size, and the CHP plant layout, among others. In this respect, an instance of analysis of the potential benefits from the use of TES in terms of improving the exploitation of CHP systems is reported in [6], where Smith et al. analyzed the economic savings derived from the addition of TES, when CHP plants provided the base load of a number of different buildings. Their cost analysis indicates that most of the times—though not always—the inclusion of TES is profitable. It must be emphasized, notwithstanding, that the focus in [6] was not on regulating the TES performance to gain an optimal profit, but on the variety of installments analyzed. In the same vein, Bianchi et al. provided an interesting comparison of TES and electrochemical storage in [7]. Their emphasis was on proving that there is a clear optimal CHP size for a given application, which depends on the storage type and size. However, their analysis elaborated neither on the uncertain features of prices and demands, nor on the regulation of the CHP + TES to achieve optimality in costs. A comparable analysis was presented in [8,9], where the authors implemented a CHP + TES system to assess the impact of dumping heat by comparing two modes of operation, with interesting conclusions about the superior profitability of operating a CHP system not always exploiting heat production. Yet neither they intended to regulate the TES operation to save primary energy, inasmuch as both reported modes of operation—with and without excess heat dumping—employed the TES as a system in which the excess heat was stored up to full capacity, without specifying stored energy management policies, possibly based on the observation of stochastic energy prices and demands. In [10], in a district heating framework, several sizes of TES were considered in an optimal dispatch problem. However, the TES regulation policy arising out of the uncertainty of energy prices and demands was not considered. That is, the problem was solved deterministically, and the TES did not play a central role in the optimization of the cost of operation. Brandoni and Renzi also described a CHP + TES format in which only the excess heat was stored, without an intentional regulation following price signals [11]. This seems to be also the case in [12]. In [13], Merkel et al. approached the sizing of a (micro-) CHP + TES plant. Their main interest was in the cost analysis, encompassing variable and capital costs to assess