Energy Conversion and Management 88 (2014) 525–534

Contents lists available at ScienceDirect

Energy Conversion and Management

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

An efficient algorithm for bi-objective combined heat and power production planning under the emission trading scheme

Aiying Rong [a,*], José Rui Figueira [b], Risto Lahdelma [c]

[a] Cemapre (Center for Applied Mathematics and Economics), ISEG, Universidade de Lisboa, Rua do Quelhas 6, 1200-781 Lisboa, Portugal
[b] CEG-IST, Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais, 1049-001 Lisboa, Portugal
[c] Department of Energy Technology, Aalto University, 00076 Aalto, Finland

ARTICLE INFO

Article history:
Received 30 May 2014
Accepted 20 August 2014
Available online 18 September 2014

Keywords:
Combined heat and power production
Multi-objective linear programming
Energy optimization
Energy efficiency
Environmental/economic dispatch

ABSTRACT

The growing environmental awareness and the apparent conflicts between economic and environmental objectives turn energy planning problems naturally into multi-objective optimization problems. In the current study, mixed fuel combustion is considered as an option to achieve tradeoff between economic objective (associated with fuel cost) and emission objective (measured in CO_2 emission cost according to fuels and emission allowance price) because a fuel with higher emissions is usually cheaper than one with lower emissions. Combined heat and power (CHP) production is an important high-efficiency technology to promote under the emission trading scheme. In CHP production, the production planning of both commodities must be done in coordination. A long-term planning problem decomposes into thousands of hourly subproblems. In this paper, a bi-objective multi-period linear programming CHP planning model is presented first. Then, an efficient specialized merging algorithm for constructing the exact Pareto frontier (PF) of the problem is presented. The algorithm is theoretically and empirically compared against a modified dichotomic search algorithm. The efficiency and effectiveness of the algorithm is justified.

1. Introduction

The increasing concerns about environmental impacts of energy production have become an integral part of energy policy planning. To combat climate change, the European Union (EU) has launched an emission trading scheme (ETS) since 2005 and has simultaneously promoted clean production technologies with smaller emissions [1]. The EU-ETS is now by far the largest emission market in the world, covering more than 11 thousand power stations and industrial plants in 31 countries, as well as airlines. The emission market utilizes the market force to reduce emission cost-efficiently.

CHP production means the simultaneous production of useful heat and electric power in a single integrated process. It can utilize the excess heat that would be wasted in conventional power production and thus can achieve higher efficiency. For example, the efficiency of a gas turbine is typically between 36% and 40% when used for power production only, but over 80% if also the heat is utilized. CHP is considered an environmentally beneficial technology due to its high energy efficiency compared to conventional separate heat and power production. This leads to significant savings in fuel and emissions, typically between 10% and 40% depending on the technique used and the system replaced [2].

Considering the fact that fossil based technologies are currently dominant [3] for supplying heat and power all over the world and CHP is an important technology to improve the energy overall efficiency of heat and power production, we study here using a fuel mix (including biomass) [3,4] as an option to implement the transition into future sustainable low-carbon energy systems. A suitable fuel mix can achieve tradeoff between economic objective (associated with fuel cost) and emission objective (measured in CO_2 emission cost according to fuels and emission allowance price) [5]. Usually, a fuel with higher emissions is cheaper than one with lower emissions. We have considered using multi-objective linear programming (MOLP) approaches to deal with a medium- or long-term CHP environmental/economic dispatch problem (EED), which can be viewed as a subproblem of long term generation expansion CHP planning problem [6]. It means that the plant characteristics are assumed to be convex. It has been commented by [7] that the convexity assumption is not as limiting as it may seem. Multiple criteria decision making approaches, including MOLP, have for a long time been used in energy planning for both traditional

---

* Corresponding author. Tel.: +351 213922747; fax: +351 213922782.
E-mail addresses: aiying.rong@hotmail.com (A. Rong), figueira@tecnico.ulisboa.pt (J.R. Figueira), risto.lahdelma@aalto.fi (R. Lahdelma).

http://dx.doi.org/10.1016/j.enconman.2014.08.049
0196-8904/© 2014 Elsevier Ltd. All rights reserved.

Nomenclature

Indices

t	index of a period or a point in time. The period t is between points $t-1$ and t. In our problem, period length is 1 h
p, q	super/subscripts or prefixes for power and heat

Index sets

J	set of extreme points of the operating regions of all components including non-generating components (e.g., contracts). ($J = \cup_{u \in U} J_u$)
J_u	set of extreme points of the operating region of component $u \in U$
U	set of all components including non-generating components

Parameters

$(\pi_{j,t},\ p_{j,t},\ q_{j,t})$	extreme point $j \in J_u$ of operating region of component $u \in U$ (fuel consumption, power, heat) in MW in period t
$c_{e,t}$	emission allowance price in €/ton for period t
$c_{\phi(j),j,t}$	Price of fuel $\phi(j)$ in €/MW at plant $u \in U$ and the same for $j \in J_u$ in period t
$c_{p\pm,t}$	power sales/purchase price in €/MW on the power market in period t
$c_{q+,t}$	heat surplus penalty cost in €/MW in period t
$\eta_{\phi(j)}$	specific CO_2 emission in ton/MW for fuel $\phi(j)$ at plant $u \in U$ and the same for $j \in J_u$
P_t	power demand in MW in period t
Q_t	heat demand in MW in period t
T	number of periods over the planning horizon

Decision variables

$x_{j,t}$	variables encoding the operating level of each component in terms of extreme points $j \in J$ in period t
$x_{p\pm,t}$	power sales and purchase volume in MW on the power market in period t
$x_{q+,t}$	heat surplus variable in MW in period t

Notation associated with multi-objective optimization algorithms

MA	merging algorithm
MDSA	modified dichotomic search algorithm
DSA	dichotomic search algorithm
Y_N	non-dominated set of the problem
$Y_{N,t}$	non-dominated set of the period t subproblem
Y_N^M	non-dominated set of the problem generated by MA
Y_N^{MD}	non-dominated set of the problem generated by MDSA
$Y_{N,\max}$	max non-dominated set of the problem, $\lvert Y_{N,\max}\rvert = 1 + \sum_{t=1}^{T}\left(\left\lvert Y_{N,t}^{M}\right\rvert - 1\right)$

power-only and heat-only systems [8–10] as well as for poly-generation including CHP systems [11]. Some recent research related to applying MOLP for dealing with poly-generation planning can be referred to [12,13].

In the long term generation expansion planning context [14], for a given investment decision, the operation subproblem, which is used to estimate operating costs, is a long term EED problem when emission impacts need to be considered. The long term EED problem can be simplified into a sequence of single period subproblems without dynamic constraints. The natural period length is typically 1 h. This simplification may be necessary for at least two reasons. First, the longer planning horizon (15 or 20 years) means that the size of the problem is large and it is difficult to handle the problem efficiently without simplification. Second, in a broader context of risk analysis where numerous scenarios need to be considered, each scenario corresponds to a deterministic long term planning problem that must be solved efficiently. Simulation based scenario analysis [15–22] is a widely used approach and the computational effort is usually large.

For the single objective case, operating costs of the multi-period planning problem without dynamic constraints can be obtained simply by summing up the results of single period subproblems. However, it is not a trivial problem in the multi-objective optimization context because typically there is no single global optimal solution. The solution process consists of identifying a representation of the Pareto frontier (PF) with a number of non-dominated outcomes in the objective space, which correspond to efficient solutions in the decision space. For the MOLP, the continuity of the PF [23] means that the number of non-dominated outcomes used to represent the PF can be rather large. Therefore, the computational effort can be huge, even though each non-dominated outcome can be obtained in polynomial time. For the bi-objective case, all of the non-dominated outcomes for representing the PF can be obtained by solving a series of weighted-sum functions. One approach is called *dichotomic search* [24] and the other approach is called *parametric simplex method* [23].

To the best of the authorś knowledge, no research is reported to deal specifically with the bi-objective multi-period CHP planning problem with no dynamic constraints. A possible reason for this may be that it is the simplest multi-period planning problem and most people think that a general solution approach can handle it. However, it is not true. An efficient solution approach to the problem is demanding in the context of risk analysis and generation expansion planning and it is not a trivial task to solve it efficiently if the planning horizon is large.

The contributions of the current study can be summarized as follows: First, we have defined a fuel mix setting for the bi-objective CHP EED problem. Second, we have presented an efficient iterative merging algorithm (MA) for constructing the exact PF for the bi-objective LP CHP planning problem on the basis of the PF for the single period subproblem. The MA utilizes the convexity of the PF by arranging slopes of two consecutive non-dominated outcomes in each period in a non-decreasing order. Third, we have conducted theoretical time complexity analysis for the MA and for a traditional algorithm to justify the efficiency of the MA. Finally, we have done numerical experiments using both real and artificially derived plants to show the applicability of the MA in practice. It is worth mentioning that the current research is a new extension of our specialized efficient algorithms for single objective optimization [25,26] to the multi-objective context and to achieve sufficient efficiency for dealing with environmental impacts taking emission costs explicitly as an objective.

The paper is organized as follows: Section 2 describes the model of the individual CHP plant as well as the model of the bi-objective CHP planning problem considering fuel mix. Section 3 presents two algorithms. The first one is a modified dichotomic search algorithm (MDSA) for a general bi-objective LP problem and the second one is a specialized merging algorithm (MA) for constructing the exact PF