Applied Energy 102 (2013) 1522–1534

Contents lists available at SciVerse ScienceDirect

Applied Energy

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

Energy production planning of a network of micro combined heat and power generators

Georgios M. Kopanos [a], Michael C. Georgiadis [b], Efstratios N. Pistikopoulos [a,*]

[a] Imperial College London, Department of Chemical Engineering, Centre for Process Systems Engineering, SW7 2AZ London, UK
[b] Aristotle University of Thessaloniki, Department of Chemical Engineering, 54124 Thessaloniki, Greece

HIGHLIGHTS

- New mathematical frameworks are developed for the operational planning of ESCNs.
- The significance of selecting a proper optimization goal is highlighted.
- Total costs: microCHP startups, operating costs, and electricity production profit.
- We introduce a novel ESCN structure wherein heat and power interchange is allowed.
- Real-life case studies show the potential benefits of the microgeneration ESCNs.

ARTICLE INFO

Article history:
Received 8 May 2012
Received in revised form 6 September 2012
Accepted 9 September 2012
Available online 18 October 2012

Keywords:
Microgeneration
Combined heat and power
Cogeneration
Energy supply chain
Energy systems
Operational planning

ABSTRACT

A promising and shortly emerging energy supply chain network based on residential-scale microgeneration through micro combined heat and power systems is proposed, modeled and optimized in this work. Interchange of electrical energy can take place among the members of this domestic microgrid, which is connected to the main electrical grid for potential power interchange with it. A mathematical programming framework is developed for the operational planning of such energy supply chain networks. The minimization of total costs (including microgeneration system's startup and operating costs as well as electricity production revenue, sales, and purchases), under full heat demand satisfaction, constitutes the objective function in this study. Additionally, an alternative microgrid structure that allows the heat interchange within subgroups of the overall microgrid is proposed, and the initial mathematical programming formulation is extended to deal with this new aspect. An illustrative example is presented in order to highlight the particular significance of selecting a proper optimization goal that thoroughly takes into account the major operational, technical and economic driven factors of the problem in question. Also, a number of real-world size case studies are used to illustrate the efficiency, applicability and the potential benefits of the microgeneration energy supply chain networks suggested in this study. Finally, some concluding remarks are drawn and potential future research directions are identified.

1. Introduction

Although many technical options exist for developing a future sustainable and more environmentally friendly energy supply chain, they are often treated separately driven by their own technical communities and political groups. In this context, *energy systems engineering* can provide a systematic model-based framework to arrive at realistic integrated solutions to the complex energy problems by adopting a holistic systems-based approach [8,10].

Nowadays, it is evident that the classical energy supply chain is rapidly changing to an energy-efficient and low-carbon energy market economy by moving towards more decentralized energy production. In accordance with the energy systems engineering perspective, there is clearly a distributed energy generation option which could play a vital role within the development of sustainable future energy systems, the energy *microgeneration*. Specifically, the most promising microgeneration technology involves the *cogeneration* (i.e., combined generation) of electrical energy and heat in small-scale energy generation units that can be directly embedded in the buildings wherein the heat and electricity are to be used. The major benefit of cogeneration systems is that their overall efficiency can be as much as 90%, while if just electricity is produced, an efficiency of no more than 40–45% could be achieved. Additionally, cogeneration networks could serve electricity markets with lower investments in the transmission and distribution

---

* Corresponding author. Tel.: +44 20 75946620; fax: +44 20 75941129.
E-mail address: e.pistikopoulos@imperial.ac.uk (E.N. Pistikopoulos).

0306-2619/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.apenergy.2012.09.015

Nomenclature

Indices/sets

$g \in G$	residential blocks
$i \in I$	households (having installed on microCHP generators)
$t \in T$	time intervals
$k \in K$	startup (or shutdown) periods

Subsets

G_i	set of residential blocks g where household i belongs to
I_g	set of households i belonging to the same residential block g

Parameters

α_i^-	number of startup periods for the microCHP of household i (in time intervals)
α_i^+	number of shutdown periods for the microCHP of household i (in time intervals)
β_i^{max}	maximum heat buffer tank capacity of household i
β_i^{min}	minimum heat buffer tank capacity of household i
$\bar{\beta}_g$	central heat buffer tank capacity of residential block g
γ_i^{max}	maximum heat generation capacity for the back-up gas burner of household i
γ_i^{min}	minimum heat generation capacity for the back-up gas burner of household i
δ_i^{on}	minimum running time for the microCHP of household i (in time intervals)
δ_i^{off}	minimum shutdown time for the microCHP of household i (in time intervals)
ε_t^{min}	minimum total electricity production for the microgrid during time interval t
ε_t^{max}	maximum total electricity production for the microgrid during time interval t
ζ_{it}^{el}	electrical energy demand for every household i at time interval t; includes electricity and cooling load
ζ_{it}^{th}	heat demand for every household i at time interval t; includes heating load and hot water
η_i	heat loss rate for the heat buffer tank of household i
$\bar{\eta}_g$	heat loss rate for the central heat buffer tank of residential block g
θ_i^{min}	minimum heat generation from the microCHP of household i
θ_i^{max}	maximum heat generation from the microCHP of household i
λ_{ik}^-	heat generation loss for the microCHP of household i during startup period k
λ_{ik}^+	heat generation excess for the microCHP of household i during shutdown period k
μ_{gi}	loss rate for interchanging heat between the central heat buffer tank of residential block g and the households i belonging to it
ν_t	tariff for the electricity exported to the macrogrid at time interval t
π_t	tariff for the electricity produced by microCHP generators at time interval t
ρ_i	electrical energy to heat production ratio for the microCHP of household i
ξ_{it}	fuel cost for operating the microCHP of household i at time interval t
ξ_{it}^{GB}	fuel cost for operating the back-up gas burner of household i at time interval t
ϕ_i	cost for starting-up the microCHP of household i
ψ_t	purchase price of electricity from the macrogrid at time interval t

Continuous variables

B_{it}	heat storage level in the heat buffer tank of household i at time t
$\bar{B}_{gt}$	heat storage level in the central heat buffer tank of residential block g at time t
E_{it}	electrical energy production by the microCHP of household i during time interval t
E_t^{buy}	electricity acquired from the macrogrid at time interval t
E_t^{sales}	excessive electricity sold to the macrogrid at time interval t
$\tilde{Q}_{it}$	heat production load level of microCHP of household i during time interval t
Q_{it}	real heat production (including loss or extra generation) by the microCHP of household i during time interval t; delivered to heat buffer tank
Q_{git}^-	heat transferred to the heat buffer tank of household i from the central heat buffer tank of residential block g, where it belongs
Q_{git}^+	heat transferred from the heat buffer tank of household i to the central heat buffer tank of residential block g, where it belongs
Q_{it}^{GB}	heat produced by the back-up gas burner of household i during time interval t

Binary variables

F_{it}	=1, if the microCHP of household i stops operating at time point t (i.e., $X_{it-1} = 1$ and $X_{it} = 0$)
S_{it}	=1, if the microCHP of household i starts operating at time point t (i.e., $X_{it-1} = 0$ and $X_{it} = 1$)
X_{it}	=1, if the microCHP of household i is operating at the beginning of time interval t
X_{it}^{GB}	=1, if the back-up gas burner of household i is operating at the beginning of time interval t

grids and with lower energy losses during transmission [18,1]. The domestic sector constitutes a key consumer of both electricity and heat, and could benefit from consolidation to meet these demands via *micro Combined Heat and Power* (microCHP) generators [9]. Several studies demonstrated that microCHP technologies can reduce significantly household energy-costs and carbon emissions, and increase overall energy utilization efficiency [7,13,5,15].

1.1. Microgeneration vs large-scale centralized generation

It is broadly alleged that microgeneration has diverse benefits over its (typical) large-scale centralized counterpart, including: (i) more efficient use of the thermal energy due to local heat generation thus maximizing the utilization of primary energy, (ii) lessened electricity transmission line load and losses, and transmission lines upgrades, (iii) reduction in the environmental footprint of producing energy, (iv) increase of the stability and reliability of the main electrical grid in electricity demand peak periods or temporal system failures, (v) a more reliable and customized operation under low maintenance needs, (vi) significant decrease in the reliance on the power companies, and (vii) reduced land use for energy generation. Also, small scale energy generation technologies can adapt better and faster to load curve variations than large ones and can ensure the possibility of finding solutions tailored to meet specific energy needs because of their scalability [11]. Overall, the centralized energy generation has been