Renewable Energy 51 (2013) 331–342

Contents lists available at SciVerse ScienceDirect

Renewable Energy

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

Optimal design and operation of distributed energy systems: Application to Greek residential sector

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ARTICLE INFO

Article history:
Received 8 July 2011
Accepted 11 September 2012
Available online 30 October 2012

Keywords:
Distributed energy resources
Heating pipeline network
Economic and operation strategies
Optimisation
Mixed integer linear programming

ABSTRACT

This work presents an optimisation based approach for the integrated plan and evaluation of Distributed Energy Resources (DER) systems. The mathematical model takes into account site energy loads, local climate data, utility tariff structure, characteristics of the candidate DER technologies (technical and financial) as well as geographical aspects. The optimal integrated DER system is selected by minimising the total energy cost while guaranteeing reliable system operation. As an illustrative example, we consider a neighbourhood in Athens (Greece), where several options for satisfying its electricity and heat demands are investigated. The adoption of DER technologies combined with a heating pipeline network and a microgrid is examined.

1. Introduction

Increasing concern regarding the depletion of fossil energy resources and the pollution of the environment, as well as the interest in on-site power generation, so as to minimise the energy losses when referring to centralised generation, has increased the importance of developing high efficiency energy generation techniques, known as distributed energy resources (DER) [1]. DER means small scale electric generation units located within the electric distribution system at or near the end-users. It is usually considered to be constructed aiming at utilising local energy resources and establishing local energy storage. Compared with traditional central energy supply, DER system can employ a wide range of technologies including: combined heat and power plants (CHP), photovoltaic systems (PV), small scale wind turbines and other systems using renewable energy resources [2]. Huang et al. [3] provided a comprehensive review of the current status of various DER technologies and discussed their operation and market environment. Carley [4] has investigated the motivators of DER adoption and the corresponding promotion policies.

Despite its numerous advantages, the incorporation of DER systems in the energy sector is not an easy task. The design and management of such a system requires the determination of its structure by selecting appropriate equipment from numerous alternatives so that they match energy requirements for a specific customer. Moreover, it is also necessary to determine the capacity of the adopted equipment as well as the operating strategies, depending on variations in energy demands.

Facing such a complex and hard task, a systematic analysis and evaluation procedure is necessary. Currently, a number of plan and evaluation models are available and have been reviewed by Hiremath et al. [5]. Some other remarkable tools include Distributed Energy Resources Customer Adoption Model (DER-CAM), which has been developed by the Ernest Orlando Lawrence Berkeley National Laboratory (LBNL) [6] and HEATMAP which has been developed by Washington State University [7]. Moreover, Manfren et al. [8] presented a methodology for the synthesis of the planning and design procedures of Distributed Generation systems by combining a number of currently available models. Hawkes and Leach [9] developed an economic optimisation model for the high level system design and unit commitment of a microgrid. Handschin et al. [10] presented a mathematical model to increase the economic efficiency of a DER system while considering the existing uncertainties. Fleten et al. [11] promoted a systems based approach

Abbreviations: CHP, combined heat power; CCHP, combined cooling, heating, power; CHCP, combined heat, cooling and power; CRF, capital recovery factor; DER, distributed energy resources; DES, distributed energy system; DG, distributed generation; DHN, district heating network; GA, genetic algorithms; HDH, heating degree-hours; HDL, heating distribution line; HSVI, hourly seasonal variation index; LHV, lower heating value; MILP, mixed integer linear programming; MGCC, microgrid central controller; MSVI, monthly seasonal variation index; PV, photovoltaic.

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http://dx.doi.org/10.1016/j.renene.2012.09.009

for evaluating the investment strategies in DER technologies while considering price uncertainty. Carvalho et al. [12] developed an MILP model for the optimal synthesis of a combined cooling, heating and power (CCHP) system subject to environmental aspects. Mancarella and Chicco [13] developed a comprehensive emission assessment framework for the distributed CHP systems, while considering partial-load characteristics. Medrano et al. [14] analysed three types of advanced DG (Distributed Generation) technologies for four types of commercial buildings from the energetic, economic and environmental points of view using the eQUEST simulation tool. Dicorato et al. [15] evaluated the contribution of DER technologies aiming to reduce environmental impact and operational costs, by integrating some energy efficient actions. Ren et al. [16] developed a mixed integer linear programming (MILP) model for the integrated plan and evaluation of DER systems, which evaluates the economic, energetic and environmental effects of the DER systems. Lozano et al. [17] developed an optimisation model to determine the preliminary design of CHCP systems with thermal storage, taking into account the legal constraints imposed on cogeneration systems in Spain.

In order to increase the efficiency of such systems and ensure their operation near their optimal load, it is important to examine possible extensions to end-applications comprised of more than just one building. By doing so, one can take advantage of the various load profiles of the buildings, compensate the fluctuations and achieve a smoother operation. It is therefore much more advantageous to implement them in a small plant that serves several buildings, and that is managed for instance by an energy service company.

Unlike district heating systems that provide only heating, district energy systems, which involve the design of a heating piping network, have not been studied to the same extent. The majority of the literature on district heating systems focuses on the optimisation of the energy conversion technologies, used in the district heating network (DHN) and their operational strategies [18–20]. However, there are a number of papers which deal with the design of the heating networks within the microgrid by using different approaches.

Soderman and Pettersson [21] have studied the design of distributed energy systems and developed a tool for decision makers. In their paper electricity loads can be satisfied through local suppliers, from the main power grid or from own production, while the thermal loads of the consumers can be satisfied with direct heat transfer from suppliers, with indirect heat transfer from heat storage, via district heating network or from own production. Their algorithm selects both sections of the main district heating network and the connection of the buildings to this line. Different types of DER technologies are considered in the model without taking into account their operational design.

Obara [22] determined the equipment arrangement of each building of the DER system and designed the hot-water piping network for supplying the exhaust heat of fuel cells and reformers to each house based on the minimisation of the total equipment, installation and operational costs, using Genetic Algorithms (GA).

Weber et al. [23] developed a hierarchical solution scheme that combines the design of the network together with the design of technologies that are best suited to meet the energy requirements of the district, considering the temperature levels at which the energy services are requested. Recently, Weber and Shah [24] proposed a single-level optimisation approach for a UK district energy system allowing mix of different energy services.

Each of the aforementioned models, found in the literature dealing with the design of DER systems, has its own characteristics. They refer to either single non-residential sites or focus on the design of the heating pipeline network, in a more detailed aspect. The overall design and operation of DER system within a microgrid in a residential scale with the incorporation of a heating pipeline network, has rarely been mentioned.

In this paper, an MILP model is proposed for the optimal DER design and operation of a Greek neighbourhood, incorporating PV and CHP units, combined with the design of the heating piping network. Thermal storage tanks have been included in this model to store excess heat, while electricity transfer is possible between the dwellings, through a microgrid which is based on the existing power transmission network. Moreover, a back-up boiler has been used, when the heating provided by the CHP unit, does not completely satisfy the application needs. Given the site's energy loads, utility tariff structure, as well as information (both technical and financial) on the PV, CHP system and the piping network, the model minimises the overall cost of the energy system by selecting the capacity of the PV and CHP system, determining their operating schedules and designing the optimal route of the heating piping network. The paper is organised as follows. A problem description is given in Section 2. In Section 3, the mathematical formulation of the proposed model is developed. Section 4 presents a numerical study to demonstrate the applicability of the proposed model, using a neighbourhood of 5 dwellings in Athens, Greece. The results are presented and discussed in Section 5. Finally, some concluding remarks are drawn in Section 6.

2. Problem description

In this problem, we consider a neighbourhood where several options for satisfying its electricity and heat demands are considered. The adoption of DER technologies combined with a heating pipeline network and electricity transmission lines is examined.

The neighbourhood consists of a number of dwellings with given electricity and heating profiles. The distances between them are also known. Every dwelling can satisfy its load by a micro-CHP (μCHP) system, a PV array, a storage tank and a back-up boiler. The μCHP system, which is driven by natural gas and the PV array are used to meet the electrical demand. The heat produced by the μCHP system is used to accommodate the thermal load. If the heating exceeds the requirement, it is sent to the storage tank to be used in subsequent periods. If the heating does not completely satisfy the application needs, a supplementary boiler can be used. There is also the possibility of heat exchange between the dwellings through a heating piping network.

When the amount of electricity generated by the μCHP system and/or the PV array in each dwelling exceeds the electricity demand, the surplus electricity is delivered back to the grid; otherwise the power utility provides the deficit electricity. We also give the option of formulating a microgrid based on the existing power transmission network. The use of a central controller allows to monitor and control the balance on the energy production and consumption of the entire neighbourhood. This means that power consumption of the neighbourhood is not billed up to point where it is satisfied by local electricity production within the neighbourhood. Extra electricity requirements are billed, while in the case of electricity surplus, this is supplied to the grid creating profit for the neighbourhood.

In the optimisation problem, the following data are given:

- Dwellings, distances between them, average 24-h hourly electricity and heat profiles for each month of the year
- Cost of PV unit, back-up boiler, CHP as a function of its capacity, cost of the heating pipeline, cost of thermal storage tanks, cost of installing a microgrid.
- Technical characteristics of DER technologies
- Average 24-h hourly electricity tariffs for each month of the year, gas price, price of selling excess electricity
- Average 24-h hourly solar irradiance profile for each month of the year