Applied Thermal Engineering 70 (2014) 211–218

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

A model for structural and operational optimization of distributed energy systems

Carl Haikarainen*, Frank Pettersson, Henrik Saxén

Åbo Akademi University, Laboratory of Heat and Flow Engineering, Biskopsgatan 8, FI-20500 Åbo, Finland

HIGHLIGHTS

- A linear multi-period optimization model of a district energy network is presented.
- Network structure and operation are optimized simultaneously.
- Optional energy suppliers, heat pipelines and heat storages are taken into account.
- A case involving an urban area is studied.

ARTICLE INFO

Article history:
Received 3 January 2014
Accepted 19 April 2014
Available online 10 May 2014

Keywords:
Optimization
District heating
Distributed energy systems
Linear model

ABSTRACT

In a world of growing concern over overconsumption and direct waste of resources, there is an urgent need to discover ways of turning the course and embracing methods of saving energy. Energy, and therefore resources, can be saved at every level of application, from the construction of machinery to the use of transportation fuel, and above all at a systems level considering how different parts and pieces come together to form structures of society. This article addresses the last issue by presenting a model for optimizing the structure and operation of a distributed energy system, or more specifically, a district heating system with its numerous alternatives for production and distribution of heat for a set of widely different consumers. Considering energy supplier technologies and locations, distribution pipe topologies, optional heat storage utilities, and varying consumer demands and weather conditions over a set of different periods, the model can calculate a structure and operational scheme for such system, displaying optimal characteristics in terms of e.g. economy or greenhouse gas emissions. Functionality of the model is demonstrated with a case study regarding the development of an urban area, and an economical optimization of its heating network.

1. Introduction

Every light that is lit, every home that is heated, every car that is driven, every process that is carried out in our society requires energy in some form. Much of the foundation of modern society is built upon a supply of energy for all the processes it encompasses, energy which to a large extent is extracted from fossil fuels formed during a span of millions upon millions of years, now sucked out of the earth's crust to satisfy human voracity. And despite knowledge and information about the dangers of overconsumption of limited natural resources spreading faster and to a wider public than ever, it is projected that the demand for energy will continue to increase for decades to come. So for many, hope is placed in the development of renewable and sustainable energy technologies to replace the fossils of old. Much is expected also from novel approaches to energy efficiency, as it has been assessed that up to half of the current primary energy use could be cut simply by adopting more efficient ways of supplying and distributing energy, and this only by taking into account economically viable options [1]. Policies are being directed along these lines, and for instance the European Union has set a goal of reducing primary energy use by 20% among its member states by 2020 [2]. It is clear that reaching these types of savings requires drastic changes in how energy is utilized today. Some of these changes could relate to how energy systems are designed as a whole.

The concept of an urban energy system has been analysed and articles on the subject have been reviewed by Keirstead [3]. A wide range of tools and mathematical models have already been developed for the sake of optimizing energy systems and integrating

* Corresponding author.
E-mail addresses: chaikara@abo.fi, carl.haikarainen@abo.fi (C. Haikarainen), frank.pettersson@abo.fi (F. Pettersson), henrik.saxen@abo.fi (H. Saxén).

http://dx.doi.org/10.1016/j.applthermaleng.2014.04.049
1359-4311/

new energy technologies into the field of distributed energy [4], with different tools applying to different situations [5]. With regard to district heating networks, operational optimization has been performed both with distinct models of specific networks [6] and by applying more general models [7]. The structural and operational optimization of district heating systems is often formulated as a mixed-integer linear programming (MILP) problem [8], sometimes dealing with multiple objectives such as simultaneous optimization of economic costs and CO_2 emissions with additional techniques such as evolutionary algorithms [9]. Some models have included more detailed attempts at optimizing the topological structure of the pipeline network involved in a district heating system [10], but they are not that common. Similarities in the problem setting can however be found, for instance, in the planning of networks of CO_2-pipelines related to carbon capture and storage technologies [11]. The purpose of this article is to present a multi-period model for structural and operational optimization of district heating systems and give examples of its usefulness as an aid in analysis and decision-making.

2. Problem description

Large parts of the inhabited world experience cold winters with temperatures commonly reaching far below the freezing point of water. These climates require buildings and residences to be heated in one way or another. While some houses have their own biomass- or oil-fired boilers, others are connected via pipelines to centralized heating plants, forming a district heating network. In these networks, water is heated at the heating plants and transported through the pipelines to consumer sites where the heat is utilized. The cooler water is then transported back to the heating plant, forming a loop. Whichever way heat is provided to the consumers, one system has to function in all the widely varying weather conditions and consumption profiles throughout the year, which makes designing the structure and operation of the system a challenging task. In such a system, improvements in energy efficiency can be reached at multiple levels of the energy chain, from how different forms of primary energy are transformed into electricity and heat to how they are distributed and how they are utilized in different applications. In the case of heating – of public and commercial buildings, homes and industries – assessing the efficiency for an entire region requires considering how every supplier operates and which technologies they employ, how the pipelines form the distribution network, how and if the buildings are connected to the district heating network or if they utilize local heat sources. These questions all need to be answered simultaneously, which is why mathematical programming techniques come into play. As long as appropriate data are available, most of the relevant relations describing a district heating network can be modelled mathematically and given treatment by optimization algorithms. In order to be able to answer a wide range of relevant questions, the models have to be flexible and quick, which calls for suitable degrees of simplification and careful considerations regarding what to include.

Of course, an optimization model can only be as good as the questions it is asked, so the objectives have to be well stated. Environmental, social and economic aspects are all relevant when dealing with energy systems, and in an ideal situation optimization models could take all of these into account.

3. The optimization model

A simulation or an optimization can only be as good as the mathematical models, parameters and data used to perform it. In the present work, the model builds upon the work of Söderman and Pettersson [12], and tries to preserve its clear structure and nimble functionality. A district heating network is assumed to consist of suppliers, consumers, heat storages and pipelines, which together form a network of nodes and edges. The problem itself consists of navigating through all the countless alternative network structures, while ensuring that the network provides sufficient heat and electricity to the consumers in a set of different periods, and that different physical and technological constraints and restrictions will not be violated. Through suitable simplification and linearization, the problem was formulated as a mixed-integer linear programme, which was found capable at providing useful information regarding possible optimal structures and operational patterns for district heating networks. Keeping the model linear was motivated by the desire to create a solvable and effective model, especially since it is expected to be further developed into a multi-objective optimization model.

Electricity is modelled as simply as possible, with consumers having a demand which is to be satisfied either by electricity from supplier nodes or from the grid, i.e. from outside the modelled network. To this is added the electricity needed by any potential heat pumps at the consumer nodes. All variables, coefficients and parameters used in the model are listed and described in Table 1. Indices used for main network components are *Si* for supplier node *i*, *Cj* for consumer node *j*, *Lm* for pipeline *m* and *Rk* for storage node *k*.

3.1. Optimization objectives

While the requirement of the district heating networks in this model is chosen as satisfying the heating demands of a set of consumers, the question of how to do so in an optimal way can be approached from several directions. The best network might as well be the one causing the least environmental damage, or perhaps the most economical one, in terms of natural resources or money. Social impacts could be thought of as suitable criteria for optimality, albeit more difficult, perhaps impossible, to quantify and measure.

Regardless of which objective is chosen, the objective function comprises investment costs related to the construction of new network components, as well as costs related to the operation of the network, written as

$$\min C = C_{\text{inv}} + C_{\text{oper}} \tag{1}$$

Both terms consist of the contributions from all the individual network components. This article will only describe an economical optimization of district heating networks, so the objective function minimises the annual amount of euros spent to deliver heat and electricity to the consumers. This represents an overall cost of the entire network, including local investments and fuel costs at the consumer sites. Situations may arise where, for instance, a district heating network run by several companies would have an overall economic optimum that would place some of the involved companies in less favourable positions than others [6]. But the aim of this type of models is to find solutions of more universal character rather than taking the view of individual stakeholders.

How the terms in the function are constructed depend on the component, for instance the investment costs of suppliers (S) depend on the type of technology chosen, so

$$C_{\text{inv},S} = \sum_{i=1}^{n_S} a_{Si} \left(\sum_{\tau=1}^{n_\tau} c_{\text{fix},Si,\tau} z_{Si,\tau} + C_{\text{SD},Si} \right) \tag{2}$$

where both the fixed costs and the size-dependent costs differ between different supplier types. For any existing supplier node, a supplier type τ has to be selected (cf. Eq. (21)), represented by the