Applied Energy 159 (2015) 161–177

Contents lists available at ScienceDirect

Applied Energy

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

Modeling and optimization of building mix and energy supply technology for urban districts

Robert E. Best *, Forest Flager, Michael D. Lepech

Stanford University, Department of Civil and Environmental Engineering, 473 Via Ortega, Stanford, CA 94305, United States

HIGHLIGHTS

- Modeled variation of building mix and energy supply technology endogenously.
- Optimized district-scale energy supply and demand simultaneously.
- Case study with CHP engines, chillers, and 21 building types run for San Francisco.
- Potential to achieve over 70% efficiency with low carbon emissions and low cost.
- Ability to provide decision support for urban planners and infrastructure designers.

ARTICLE INFO

Article history:
Received 28 March 2015
Received in revised form 14 August 2015
Accepted 17 August 2015

Keywords:
District energy systems
Multiobjective optimization
Genetic algorithm
Combined heat and power
Energy modeling

ABSTRACT

Reducing the energy consumption and associated greenhouse gas emissions of urban areas is paramount in research and practice, encompassing strategies to both reduce energy consumption and carbon intensity in both energy supply and demand. Most methods focus on one of these two approaches but few integrate decisions for supply and demand simultaneously. This paper presents a novel model that endogenously simulates energy supply and demand at a district scale on an hourly time scale. Demand is specified for a variety of building uses, and losses and municipal loads are calculated from the number of buildings in the district. Energy supply is modeled using technology-specific classes, allowing easy addition of specific equipment or types of energy generation. Standard interfaces allow expansion of the model to include new types of energy supply and demand. The model can be used for analysis of a single design alternative or optimization over a large design space, allowing exploration of various densities, mixes of uses, and energy supply technologies. An example optimization is provided for a community near San Francisco, California. This example uses 21 building types, 32 combined heat and power engines, and 16 chillers. The results demonstrate the ability to compare performance trade-offs and optimize for three objectives: life cycle cost, annual carbon dioxide emissions, and overall system efficiency.

1. Introduction

1.1. Motivation

Cities occupy 3% of the earth's land area, yet consume 75% of natural resources and produce 60–80% of global greenhouse gas emissions [1]. These impacts will grow as urbanization increases from 54% of world population today to 66% by 2050 [2]. In the United States, urban buildings and infrastructure consume 33% of energy and produce 40% of national greenhouse gas emissions [3]. This drives a need to reduce emissions, which comes at a cost; the Intergovernmental Panel on Climate Change Fourth Assessment Report projected that buildings and fuel switching can reduce greenhouse gas emissions 36–56% by 2020 at a cost ranging from \$0 to \$100/ton CO_2 [4].

A common response is to address energy supply and demand independently through regulation and voluntary certification. In practice, a proliferation of voluntary and prescriptive green building codes (e.g., Leadership in Energy and Environmental Design (LEED) [5], Living Building Challenge [6], California Green Building Standard [7]) have attempted to improve the efficiency of new and retrofitted buildings through quantitative and

* Corresponding author at: John A. Blume Earthquake Engineering Center, Stanford University, 439 Panama Street, Stanford, CA 94305, United States. Tel.: +1 (818) 456 6919.

E-mail addresses: robbest@stanford.edu (R.E. Best), forest@stanford.edu (F. Flager), mlepech@stanford.edu (M.D. Lepech).

http://dx.doi.org/10.1016/j.apenergy.2015.08.076
0306-2619/

qualitative standards. Reducing the carbon intensity of energy supply has involved a combination of renewable energy mandates and financial incentives [8]. However in both research and practice, few methods exist to help planners and policymakers trade off solutions for balancing energy supply and demand interventions simultaneously.

Balancing energy supply and demand can also happen at a local district or community scale. Herein, "district or community scale" is defined as 10^2–10^3 neighboring buildings with peak power consumption generally on the order of 10^1–10^2 MW; this is similar to the scale of district networks examined by Rezaie and Rosen [9]. A recent proliferation of rating systems has attempted to incentivize sustainable community development through point-based certification (e.g., LEED for Neighborhood Development [10], Sustainability Tools for Assessing and Rating Communities [11]). However these systems lack a comprehensive method for valuing tradeoffs between demand and supply interventions. This is in part because of a lack of modeling ability; a survey of urban energy system models by Keirstead et al. [12], showed that only a small number of models consider energy supply and demand endogenously, with the majority using qualitative decision making techniques rather than quantitative evaluation of economic and environmental benefits. This paper describes one approach to balancing interventions in energy demand and supply and valuing the environmental and economic benefits.

1.2. Prior research

A review of literature on urban and community energy system models revealed the following four criteria for a tool to be useful in balancing urban planning and energy infrastructure development. An ideal tool should:

(1) *Endogenously simulate and vary energy supply and demand:* Keirstead et al. [12], following the definition laid out by Jaccard [13], emphasize that an urban energy model should capture both supply and demand within a local context considering energy production, storage, transportation, and conversion to end service.
(2) *Be capable of accurately assessing the dynamics of energy systems at a district or community scale:* Jaccard [13] stressed that the scale for simulation must be community-based to capture the observed gaps in supply and demand modeling and to match the scale of planning and zoning.
(3) *Simulate on no greater than an hourly time scale:* Evins et al. [14] and Hawkes and Leach [15] showed that networked systems require hourly analysis to capture spikes in demand and ramping effects of generators that can dramatically impact performance and efficiency.
(4) *Be easily adapted to new energy supply and building technologies:* Van Dam and Keirstead [16] and Manfren et al. [17] argued that an urban energy model must be capable of incorporating a broad spectrum of technologies and should leverage existing methodologies through a common ontology.

Existing tools and methods documented in literature generally address only a subset of these characteristics and can be characterized by their focus on community or district-scale energy supply optimization, building and urban energy demand modeling, and combined energy supply and demand models.

1.2.1. Energy supply literature

Community energy supply modeling predominantly involves simulation and optimization of district heating and cooling systems. Liu et al. [18] provides an overview of combined cooling, heating and power (CCHP) technologies and systems that have been implemented at the community scale as well as the management, control and optimization of these systems. Vasebi et al. [19] and Merkel et al. [20] examine dispatch of an interconnected, community-scale grid powered by multiple combined heat and power (CHP) plants; Evins, Pointer, and Vaidyanathan devised a similar approach using a logic tree and a harmony search algorithm (2011). Casisi et al. [21] extend from purely dispatch to include optimization of location of CHP microturbines and a central power plant in Italy. Chinese and Meneghetti [22] use a mixed integer linear program to optimize deployment and operation of boilers in an Italian district heating system. Nuytten et al. [23] presents a method to determine the theoretical maximum of flexibility of district CHP systems and discusses the implications for various energy storage concepts for a reference district. Many studies have also examined planning and economics of district energy systems. Gustafsson and Karlsson [24], Fu et al. [25], and Sugihara et al. [26] simulated district heating systems using CHP plants in Sweden, China, and Japan, respectively. All three showed that cost and energy could be reduced by approximately 20%. Courchesne-Tardif et al. [27] used the TRNSYS software to simulate community-scale district heating and solar thermal under various policy scenarios. Keirstead et al. [28] examined the effect on system cost and energy efficiency of different policy restrictions on CHP plant location using a mixed integer linear program. Orehounig et al. [29] describes a method of decentralized energy systems at neighborhood scale using the energy hub concept, which is used to study a variety of energy supply configurations for a village in Switzerland considering energy autonomy and CO_2 emissions. In addition to these studies, Connolly et al. [30] identified 37 software tools currently available for planning or evaluating distributed energy resources, CHP installations, and district energy systems. They noted large diversity among these tools in scale of analysis, technologies considered, and objectives evaluated. Yet a common thread in these tools and the aforementioned studies is the focus on supply without the ability to modify or examine the impact of energy demand on cost, efficiency, and environmental impact.

1.2.2. Energy demand literature

Energy demand modeling often has taken the form of simulating individual buildings using available software packages (e.g. EnergyPlus, eQuest, TRACE) [31]. In some cases this has been extended to parametric evaluation of building performance [32] or to optimize building form to minimize cost and environmental impact [33]. Nguyen et al. [34] provides a comprehensive review of simulation-based methods the have been applied to optimize energy performance at the building scale. Yao [35] studied how to optimize the building design for different housing units to minimize both the total demand of the development as well as the differences in consumption between individual housing units. Salat [36] used building energy modeling to demonstrate the role of massing and neighborhood morphology on individual building energy consumption. However, in general, Markovic et al. [37] found that no existing energy modeling tools assess community energy demand and the impact of policy scenarios. Jennings et al. [38] created a model to examine the deployment and impact of policies governing thermal and electrical energy retrofits for houses in London using a mixed integer linear program. From an urban planning and energy system perspective, Chow et al. [39] examined the mix of five building types that optimally diversified cooling load to maximize the efficiency of a district cooling system in Hong Kong. Fonseca and Schlueter [40] characterized electricity, heat, and cooling consumption patterns of buildings over a year to understand the role of location and building type in consumption. They used this to suggest energy efficiency upgrades and participation in district heating loops to reduce energy consumption and