Energy and Buildings 92 (2015) 306–312

Contents lists available at ScienceDirect

Energy and Buildings

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

A comparative study of district and individual energy systems providing electrical-based heating, cooling, and domestic hot water to a low-energy use residential community

Magdalena Brum [a,b,*], Paul Erickson [a], Bryan Jenkins [c], Kurt Kornbluth [b,c]

[a] Department of Mechanical and Aerospace Engineering, University of California, Davis, CA, United States
[b] Program for International Energy Technologies, University of California, Davis, CA, United States
[c] Department of Biological and Agricultural Engineering, University of California, Davis, CA, United States

ARTICLE INFO

Article history:
Received 8 October 2014
Received in revised form 8 January 2015
Accepted 21 January 2015
Available online 30 January 2015

Keywords:
District energy
Low-energy buildings
TRNSYS

ABSTRACT

This study analyzes potential benefits of centralized systems providing space conditioning and domestic hot water to a small community of electric-only low-energy use dwellings in Northern California. Benefits are analyzed in terms of levelized cost and site energy use. Two district-based scenarios, served by a central ground source heat pump and a central electric boiler with individual air conditioning units, are compared against a decentralized business as usual scenario with individual electric space heaters, air conditioning units and storage-type electric water heaters. Electricity use and levelized cost were modeled in TRNSYS. For a 3-dwelling system with total thermal energy demand of 14.2 MW h/y and peak load of 12.7 kW, the district ground source heat pump configuration uses less electrical energy and power. However, the business as usual system has the lowest levelized cost due to the high cost of the ground-source heat pump installation. Levelized cost was most sensitive to capital cost and number of dwellings connected to the system for the district configurations considered. A 30% decrease in capital cost of the district system resulted in 21% average decrease of levelized cost, while a 100% increase in the number of dwellings resulted in an average 17% decrease of cost.

1. Introduction

Thermal energy services such as domestic hot water and space conditioning are the predominant energy demands of low-energy use dwellings. Reducing energy use in these dwellings presents special challenges as the cost-effectiveness of energy efficiency measures is compromised by diminishing returns from increasing capital expense. District energy systems (DES), which are centralized systems that produce and deliver thermal energy to multiple users, may allow for cost-effective reductions of energy use in low-energy use housing units. The driver for establishing a district supply is the possibility of obtaining higher efficiency, and thereby lower operating costs, when converting thermal energy in a few large plants than when using small individual units with the same total capacity. However, these benefits are usually associated with high up-front capital costs for the district systems. Thus, investment decisions for district systems consider the trade-off between operating and investment costs, typically through comparisons of the levelized cost of energy (LCOE). This study investigates small scale district energy systems for low-energy dwellings and the conditions under which the district systems potentially increase energy efficiency and decrease the LCOE with respect to a business as usual individual configuration. Specifically the low energy dwellings are based on the UC Davis Domes Student Housing, a 12-dwelling community in Davis, California that has electricity as the only site energy source. The dwellings are 57.8 m^2, including loft area, and are considered low-energy units (total energy use ≤120 kW h/m^2 year).

2. Literature review

A great portion of the literature on DES focuses on the development of simulation and optimization models to handle the complexities of these systems. This includes generic software tool applications, using a system approach for feasibility and performance analysis [1,2], models for load forecasting [3,4], design and analysis of specific components [5,6], operation optimization

* Corresponding author at: University of California Davis, Program for International Energy Technologies, 1605 Tilia St. suite No. 100, Davis, CA 95616, United States. Tel.: +15307524909.
E-mail address: magdalenabrum@gmail.com (M. Brum).

http://dx.doi.org/10.1016/j.enbuild.2015.01.045
0378-7788/

Nomenclature

AEC	annual electricity consumption of the thermal energy system (kW h/year)
ADS	annual delivered service (kW h_{th}/y)
ASHP	air source heat pump
AWHP	air to water heat pump
BAC	central Boiler and individual air conditioners scenario
BAU	business as usual scenario
CC	capital cost ($)
CRF	capital recovery factor
CoE	cost of electricity ($/kW h_e)
DES	district energy system
DHW	domestic hot water
GHP	ground source heat pump
i	interest rate
LCOE	levelized cost of thermal energy ($/kW h_{th})
n	project lifetime (years)
ND	number of dwellings in the system
OM_f	fixed lifetime operation and maintenance costs
Q_c	cooling load (kW)
Q_H	heating load (kW)
Q_S	annual thermal energy supplied or removed in case of cooling (kW h_{th}/y)
Tamb	dry bulb ambient temperature
TCSP	cooling temperature setpoint
TDHW	domestic hot water temperature
TH1SP	first Stage heating temperature setpoint
TH2SP	second Stage heating temperature setpoint
Tind	indoor temperature of dwelling
TRNSYS	transient System Simulation software

and system control [7–10] and cost analysis [11]. Several studies present models for assessment of specific case studies [12–15].

Economic feasibility and optimization have consistently been the main objectives of DES studies, typically through an LCOE analysis. A main parameter used to relate the feasibility of DES with respect to LCOE is the linear heat density (LHD), defined as the ratio of annual thermal energy supplied (Q_S) to the total trench length of the district heating pipe system (L), expressed in MW h/m y [24]. Typically, the higher the LHD, the more economically attractive a district system is, although the system is constrained by the heat dissipation capacity. Recent studies [16] show that the current trend towards increasing building efficiency and low energy buildings challenges the low operating costs of DES as the relative transmission energy losses increase. This translates into reduced LHDs. At a given LHD value, a limit is reached where it is no longer competitive to supply thermal energy through a DES. Case studies in Europe and Canada [16–19] indicate LHD limit values between 0.20 and 3.0 MW h/m y.

In terms of comparing site energy use of DES and individual systems, two previous studies can be related to the present one. A Canadian work [20] analyses several scenarios providing 9600 MW h/y of thermal energy to 8456 m^2 of mixed used buildings. Scenarios included an all-electric individual system with baseboard heaters and split type air conditioners, as well as a ground source heat pump DES. Site energy was reduced by 23% in the DES case. A Japanese study [21] compared an electric heat pump DES with an individual air source heat pump system. Thermal energy supplied was of 41,200 MW h/y and total building area was 415,000 m^2. Site energy savings were of 29%.

All the cases presented in this section, deal with DES serving at least hundreds of buildings, usually of mixed residential and commercial use, most located in Europe. This study is focused on very small systems, on the order of a dozen low-energy units, serving only residential dwellings, each with an annual thermal energy demand of 5000 kW h_{th} and located in Northern California. The main purpose of this study is to understand under which conditions a DES for these type of applications increases energy efficiency and decreases the levelized cost of energy service (LCOE) with respect to a business as usual individual configuration. The parametric study in this paper provides simulation data to understand district systems trends at very small scales, as well as the main barriers to widespread use of such small DES in California.

3. Methods

3.1. Modeling

Using the TRNSYS transient thermal modeling and simulation software environment [22], three scenarios were built using different sets of technologies, two of them are small district systems and one is a business as usual (BAU) decentralized system, in which each dwelling is served by its own set of equipment (Table 1). The models are based on the UC Davis Domes Student Housing, a 12-dwelling community in Davis, California that has electricity as the only site energy source. The dwellings are of a hemispherical (dome shape) architecture each with a floor area of 57.8 m^2 including loft area. They are also designed as low-energy units with total energy use ≤120 kW h/m^2 year. Weather data from the standard format Typical Meteorological Year version 3 (TMY3 [23]) for Sacramento, California, were used for simulations.

3.1.1. Dwelling model

TRNSYS Type 56 was used to model the thermal behavior of the dwellings. As a simplified approach, each dwelling was modeled as a single thermal zone with external boundary walls, assuming 7.6 × 7.6 × 2 m (length, width, height) prismatic structures with the same total floor area and volume as the reference dwellings, which are singular hemispherical dome-shaped constructions, as shown in Fig. 1.

Table 2 summarizes dwelling model parameter values and sources. The heat transfer between the concrete slab and the soil was modeled through a ground-coupling component (Type 703), which assumes conductive-only heat transfer, with no moisture effects. The inputs are the slab U-value and the soil properties, corresponding to the reference community location.

3.1.2. HVAC and domestic hot water equipment

Main assumptions for equipment models for all scenarios are summarized in Table 3.

Space conditioning in the GHP scenario is delivered by two 2-pipe hydronic fancoils (Type 697), one for heating and one for cooling. The coils are fed conditioned water by the central unit. Catalog data (UniTrane Fancoil FC-D-020, [29]) are used to provide coil performance as a function of entering air and fluid conditions. The BAC scenario is similar, but with only one fancoil unit used for space heating delivery.

The dynamic behavior of the ground loop serving the heat pump in the GHP scenario is modeled by a vertical U-tube ground-coupled heat exchanger (Type 557). For this model, the average ground temperature is assumed to be unaffected by system operation previous to the simulation period (no preheating). Parameters for the ground heat exchanger (Table 4) are based on engineering contractor data [28] (Fig. 2).

3.1.3. Controls and demand profiles

The HVAC demand profile is given by the space conditioning equipment control system, which has three components: a season