Investigating the Potential of Residential District Energy

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ABSTRACT

The International District Energy Association claims that district energy: improve energy efficiency, enhanced environmental protection, fuel flexibility, ease of operation and maintenance, reliability, comfort and convenience for customers, decreased life-cycle costs, decreased building capital costs, and improved architectural design flexibility. In the U.S.A. most of the installed district energy systems are found in buildings such as colleges and universities, healthcare installations, government installations, airports and community utilities, as well as industry. All these applications have proved the advantages of district energy. However, for typical neighborhoods in small cities in the U.S.A., the dispersion of the dwelling imposes additional challenges to the economic feasibility of district energy for residential applications. This paper presents results from the analysis of comparing single homes with standard HVAC systems (air conditioning and furnace) with the same homes connected to a hypothetical residential district energy system. In order to obtain the energy consumption of the standard HVAC and of cooling and heating loads for the simulation of the district energy, the software Building Energy Optimization (BEopt) was used to simulate a hypothetical home. The analysis is based on a variable number of residences coupled to the district energy system in order to determine the operating costs and capital costs as a function of the number of homes. Results show that the capital cost associated to the central utility plant decrease with the number of homes and the payback period is somewhat favorable. However, the cost of the 4 pipes hydronic system imposes a large cost to the district energy system that compromises its economic feasibility. In order to investigate the impact of the piping system on the overall capital cost of the district energy system, a hypothetical layout is considered and used as a reference to estimate the needed piping cost per home to meet a payback period.

INTRODUCTION

The International District Energy Association, in its website [1], states “District energy systems produce steam, hot water or chilled water at a central plant. The steam, hot water or chilled water is then piped underground to individual buildings for space heating, domestic hot water heating and air conditioning.” This type of system has been implemented in the U.S.A. in different applications. Based on 2009 data, the 837 systems reported in the U.S. are distributed as Colleges and Universities 400, Community Utilities 119, Healthcare Installations 251, Military/Gov Installations 41, Airports 10, Industrial 13, other 3 [2]. The community utilities refer to downtown utilities.

District energy systems embrace efficient and renewable energy technologies, including combined heat and power, solar hot water, biomass, and thermal storage, among others. These technologies make possible to achieve benefits such as improved energy efficiency, fuel flexibility, and reliability. However, this study is limited to the consideration of the use of an efficient electric chiller with variable speed and a boiler using natural gas to provide chilled water and hot water, respectively.

As the authors’ first approach to investigate the potential of district energy in residential buildings, a simplified system and analysis was developed. For the economic analysis, the simple payback period (SPB) is used to investigate the economic N. Fumo is an associate professor in the Department of Mechanical Engineering, The University of Texas at Tyler, Tyler, Texas, USA. V. Bortone is a Project Development Consultant, Johnson Controls Inc., Lenexa, Kansas, USA. J. Zambrano and A. Zambrano are associate professors, Universidad Nacional Experimental del Táchira, San Cristóbal, Táchira, Venezuela.
feasibility of the system comprised of a central utility plant and piping distribution system. The plant consists of an electrical chiller and a boiler to supply chilled water and hot water, with their ancillary equipment. Although a net present value approach may be a more appropriated economic metric for this type of projects, the SPB period is used mainly to compare the equipment cost that would be translated to the homeowner by the developer.

**APPROACH**

A reference home is used to estimate energy consumption and equipment capital cost. Although it is clear that identical homes will not have the same energy consumption due to different schedules of occupancy and internal loads, as well as preference on thermostat setpoints among other variables, in this study it is assumed that all homes have identical hourly loads and energy consumption. This assumption is made to simplify the analysis, but at the same time it can be considered as the most adverse case since for non-coincident loads, the district energy system can be smaller and operate at a higher overall energy efficiency.

**Reference Home**

The systems capacities and energy consumption are obtained using a reference hypothetical home (RHH). The software BEopt [3] version 2.0.0 was used to develop a model to obtaining the electricity and natural gas consumption, as well as the cooling and heating loads. The simulation of the district energy system was performed using code developed for this research, and it is described in Section “District Energy Model.”

This section presents parameters describing the RHH. Any parameters needed by the software that are not described in this section match those of the Building America Benchmark (B10 Benchmark) which defines a new construction (2010) building, based on the 2009 IECC code. More information on the B10 Benchmark can be found on Ref. [4]. Some specifications used for the development of the model and perform simulations are:

- Slab dimensions: 15 m (50 ft) by 15 m (50 ft); with 3 bedrooms and 2 bathrooms (front faces North)
- Garage area: 6.1 m (20 ft) by 6.1 m (20 ft) (located on the front left corner)
- Wall Height: 3 m (10 ft)
- Attic: unfinished attic over the house and garage
- Roof Type and Pitch: Hip and 10:12
- Location is Tyler, TX (weather file: USA_TX_Tyler-Pounds.Field.722448)
- Air conditioning COP 3 and furnace efficiency 80%

The homes connected to the district energy system differ only from the RHH on the substitution of the HVAC equipment by an air handler unit. The ducts of the air distribution system are identical.

**Neighborhood layout**

Preliminary analysis indicates that the piping system is a major factor affecting the economics of the district energy system. In this study it was assumed that the homes in a new neighborhood will have the layout shown in Figure 1. For the analysis, the number of homes increases from the central utility plant (CUP) through the main line along the street. As it can be noticed, sections of pipes with 15 m length are added for each two homes.

Due to the large different diameters that can be found for analysis of large number of homes, to compute the capital cost and pumping energy consumption, an average normalized diameter was used for the main pipe line along the street.

**District Energy System**

The district energy system is compressed of an electric chiller, cooling tower, boiler, and pumps located on the
building of the CUP, and the distribution system (piping system) supplying chilled and hot water to the air handler units (AHU). Figure 2 illustrates a schematic of the systems.

**Figure 1** Neighborhood layout.  
**Figure 2** Schematics of the district energy system.

**Cooling system**

Chilled water is produced by an electrical centrifugal chiller, which includes a variable speed drive (VSD). The nominal efficiency of the chiller is estimated to be 0.45 kW per ton of refrigeration (TR). The temperature difference for the chilled water is set to be 6.5 °C (~12 °F). The flow rate is proportional to the number of houses. Heat transfer losses along the pipes are neglected in this study since the pipe is buried underground. The chiller uses a cooling tower with variable speed fan to keep the chiller cooling water at a constant inlet temperature.

**Heating system**

Hot water is produced using a boiler. The boiler fuel efficiency is estimated to be 85%. The design temperature difference for the hot water is set to be 14.0 °C (~60 °F). The flow rate is proportional to the number of houses.

**Air Handler Unit**

Each home has its own 4 pipes AHU connected to the chilled water loop, hot water loop, and the air distribution. Chilled water needed to satisfy the cooling demand is controlled by a 2 way-valve with temperature setpoint of 12.8 °C (55 °F) (6.5 °C above the constant chilled water inlet temperature). Hot water needed to satisfy the heating demand is controlled by a 2 way-valve with temperature setpoint of 82.2 °C (180 °F) (13.9 °C above the constant hot water inlet temperature).

**Hydronic system**

The hydronic system consists of the pumps located in the plant and the piping system. Pumps are assumed to be variable speed to manage the variable flow rates. Pump efficiency is assumed to be constant at 0.54 (0.6 pump efficiency and 0.9 motor efficiency). The pipes are steel with an estimated roughness of 152 μm. The water velocity is set at 1 m/s for pipes running from the main line along the street to the AHU, 2 m/s average for pipes of the main line along the street, and 2.5 m/s for the pipes from the closets home to the CUP. A 30% of friction losses are assumed for minor (fittings) losses.

**DISTRICT ENERGY MODEL**

**Cooling system**

The chiller hourly cooling demand \( \dot{Q}_{C_{H_{AHU}}} \) is computed based on the home’s hourly cooling demand \( \dot{Q}_{C_{H_{i}}} \) and the
number of homes \((N)\) connected to the system
\[ CH_{dt} = N \hat{Q}_{ct} \]  
(1)
where \((t)\) corresponds to the hour of analysis based on the 8,760 hours of the year.

The chiller nominal capacity \((CH_{cap})\) is defined as the maximum cooling demand based on the number of homes
\[ CH_{cap} = N \max(\hat{Q}_{ct}) \]  
(2)

The chiller hourly part-load efficiency \((\eta_{ch_t})\) is computed based on the chiller nominal efficiency \((\eta_{ch.n})\) and the hourly part-load-factor \((PLF_{ch_t})\) as
\[ \eta_{ch_t} = \eta_{ch.n} \cdot PLF_{ch_t} \]  
(3)

The hourly part-load-factor is estimated based on the hourly partial-load-ratio \((PLR_{ch_t})\) and the efficiency curve shown in Figure 3, which is adapted from Ref. [5] for a condenser-water temperature of 65 °F. Since the chiller capacity is defined based on the maximum cooling demand, which may occur only during a few hours during the year, it is expected that the chiller will operate most of the time at a part-load ratio lower than 0.8.

![Figure 3 Chiller Part-Load Factor Curve.](image)

The hourly partial-load-ratio is computed as
\[ PLR_{ch_t} = \frac{CH_{dt}}{CH_{cap}} \]  
(4)

The hourly chiller electricity consumption \((EL_{ch_t})\) is computed as
\[ EL_{ch_t} = CH_{dt} \cdot \eta_{ch_t} \]  
(5)

The hourly cooling tower electricity consumption \((EL_{ct_t})\), due to condensing pumps and fans, is assumed to be a fraction \((f_{ct})\) of chiller electricity consumption, 10\% in this study,
\[ EL_{ct_t} = f_{ct} \cdot EL_{ch_t} \]  
(6)

**Heating system**

The hourly thermal energy needed from the boiler \((\dot{Q}_{bt})\) is proportional to heating demand \((\dot{Q}_{ht})\) and affected by the boiler fuel efficiency \((\eta_{b})\)
\[ \dot{Q}_{bt} = \frac{\dot{Q}_{ht}}{\eta_{b}} \]  
(7)

**Hydronic system**

The hourly volumetric flow rate \((\dot{V})\) at each house is computed based on the cooling or heating demand and the temperature change across the cooling \((\Delta T_c)\) or heating \((\Delta T_h)\) coils as
\[ \dot{V}_{ct} = \frac{\dot{Q}_{ct}}{c_p \rho \Delta T_c} \quad \text{or} \quad \dot{V}_{ht} = \frac{\dot{Q}_{ht}}{c_p \rho \Delta T_h} \]  
(8)
The volumetric flow rate is increased for the street lines based on the number of homes been fed by the street line, until the section going into the plant for which the flow rate becomes $N\dot{V}$.

The distribution pump power ($P_p$) is computed as

$$P_{p,c} = \dot{V}_c \gamma H_{c_t} \quad \text{or} \quad P_{p,h} = \dot{V}_h \gamma H_{h_t}$$  \hspace{1cm} (9)

where $\gamma$ is the water specific weight (assumed constant at 1000 kgf/m$^3$), and $H$ ($H_{c_t}$ or $H_{h_t}$) is the total head loss for the cooling or heating loops.

The total head loss is computed as the sum of all head losses on the loop

$$H = H_f + H_{fit} + H_{coil} + H_{eq}$$  \hspace{1cm} (10)

where $H_f$ is the head loss due to friction, $H_{fit}$ is the head loss due to fittings (30% of $H_f$), $H_{coil}$ is the head loss at the AHU cooling or heating coil (4.6 m/15 ft), and $H_{eq}$ is the head loss at the equipment used to produce the chilled water (chiller) or hot water (boiler). For this study, $H_{eq}$ is assumed 15.2 m (50 ft) at the chiller and boiler.

The hourly energy consumption from the pumps is computed accounting for the pump efficiency

$$El_{p_t} = \frac{P_p}{\eta_p}$$  \hspace{1cm} (11)

**Grid electric power**

The annual electricity purchased by the CUP to operate all equipment is estimated as

$$El_{grid} = \sum (El_{ch_t} + El_{c_t} + El_{p_t})$$  \hspace{1cm} (12)

**Fuel consumption**

In this study, natural gas (NG) is used as fuel with a heating value ($HV$) of 1027 Btu/ft$^3$. Therefore, the annual fuel consumption of NG is estimated as

$$F_{NG} = \sum \frac{\dot{q}_{bt}}{HV} = \sum \frac{\dot{q}_{bt}}{1027}$$  \hspace{1cm} (13)

**ECONOMIC PARAMETERS**

This section presents parameters and criteria used to perform the economic analysis. When no information is given on the source of the information presented, it means that the parameters and criteria are based on experience of the authors.

**Home System**

A preliminary analysis allowed to consider that the total installed cost of the standard HVAC system can be compared with the cost of the installed system (AHU and pipes) needed by the district energy system. Therefore, their costs are equivalent and consequently not necessary to be included to estimate the SPB.

**Central Utility Plant**

Since the size of the equipment will vary with the number of homes served by the CUP, equations of cost as a function of capacity were used. The equations were obtained from curve fits of data from a specialized manual of costs [6].

- Chiller (capacity, $Cap$, in tons of refrigeration): $S = Cap[2124(Cap)^{-0.19}]$  \hspace{1cm} (14)
- Cooling tower (capacity, $Cap$, in ton of refrigeration): $S = Cap[2556(Cap)^{-0.358}]$  \hspace{1cm} (15)
- Boiler (capacity, $Cap$, in 1000 Btu per hour): $S = Cap[675(Cap)^{-0.373}]$  \hspace{1cm} (16)
- Pumps (capacity, $Cap$, hp): $S = Cap[9193(Cap)^{-0.561}]$  \hspace{1cm} (17)

The cost of pipes varies with diameter and is given per linear meter of 4 steel pipes, 2 for chilled water and 2 for hot
water. The costs include trench to bury the pipes, as well as the cost of fittings and welding the pipes. The costs are estimated based on the assumption that the neighborhood is a new development. On the other hand, the cost of the pipes of the main line along the street is estimated using the average normalized diameter as mentioned previously.

### Table 1. Piping costs

<table>
<thead>
<tr>
<th>Diameter (inches)</th>
<th>Cost ($/m)</th>
<th>Cost ($/ft)</th>
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<tbody>
<tr>
<td>2</td>
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<tr>
<td>4</td>
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<tr>
<td>12</td>
<td>5110</td>
<td>1558</td>
</tr>
</tbody>
</table>

The cost of the building of the CUP is estimated based on capacity of chiller (includes the cooling tower) and boiler as

$$
\$ = \left( 1.65 \frac{n^2}{\text{ton Cap}} \right)_{\text{chiller}} + \left( 0.12 \frac{n^2}{\text{MBH Cap}} \right)_{\text{boiler}} 150 \frac{\$}{n^2}
$$

### Rates

- The electric rate for the reference home is assumed at $0.1117/kWh [7], which corresponds to the average residential retail price for Texas during September 2012.
- The natural gas rate for the reference home is assumed at $12.36/1000 ft³ [8], which corresponds to 2012 annual average for residential consumers in Texas [10].
- The electric rate for the CUP is assumed at $0.0817/kWh [7], which corresponds to the average commercial retail price for Texas during September 2012.
- The natural gas rate for the CUP is assumed at $6.59/1000 ft³ [9], which corresponds to 2012 annual average for commercial consumers in Texas.

### RESULTS AND DISCUSSION

Preliminary results showed that the cost of the 4 pipes of the main line to which the homes are connected involves a large cost that makes difficult the district energy system to compete with the standard HVAC system from an economic point of view. To illustrate this, Figure 4 shows the variation of capital cost for the chiller, cooling tower, boiler, and CUP building as a function of the number of homes. As expected from the equations of costs for the CUP, for all equipment the capital cost per home decreases as the number of homes increases with a trend towards an asymptotic value. The building cost remains constant independent of the number of homes due to the assumption that (1) the systems must handle the maximum cooling and heating loads, and (2) all homes have the same hourly energy consumption, (3) the system capacity is found as the product of the maximum capacity and the number of homes, and (4) the building cost is proportional to the equipment capacity.

From Figure 4, the total capital cost without the piping system should follow a similar trend to the curve of the chiller. However, Figure 5 shows that the total capital cost of the district energy system follows the trend of the piping system cost. It can be noticed that the number of homes in the abscissa starts at 150 homes, which is the estimated number homes that will give enough cooling demand to justify an available chiller with the characteristics considered in this study. The shape of the curve for the piping system is defined by the average normalized diameter used to estimate the cost of the pipes of the main line along the street. Since the water velocity is constant (2 m/s for the main line pipes along the street), the diameter of the pipes and consequently the piping cost will be constant until a new diameter is needed to avoid exceeding the design water velocity. The total capital cost of the district energy system follows the trend of the piping system because the cost of the piping system contributes with at least 75% to the total cost (percentage increases with pipe diameter).
Figure 6 shows the SPB and operation costs as a function of the number of homes. The shape of the operating cost is explained by the average normalized approach used to dimension the pipes for the main line along the street. While the diameter of the pipes is constant, as the number of homes increases, the head losses and consequently the operating costs associated to the pumps increase. When a change on diameter is needed to avoid exceeding the maximum design velocity, the velocity decreases and consequently the head losses and relative operating costs variation associated to the pumps decrease. Regarding the SPB curve, when the diameter of the pipes is constant, the capital cost and operating cost variations are proportional making the SPB to remain approximately constant. However, for a change in diameter, the variation in capital cost of the pipes increases while the relative operating costs variation decrease making the SPB to increase.

As mentioned and illustrated by the results, the capital cost of the piping system is the key factor defining the economic feasibility of a residential district energy system. Therefore, options to reduce the cost should be considered at the design stage. The following are some options that could be considered:

- Installation of pipes when other services are installed to distribute the cost of burying the pipes.
- Implementation of the district energy system in multifamily buildings instead of single homes.
- Use of a two pipes distribution system instead of a four pipes system. This option may reduce the cost of piping by half, but decreases the thermal comfort.
- The use of PVC or other materials instead of steel.
- Optimization of the neighborhood layout and piping system.

For the parameters, constrains, and assumptions used in this study, Figure 7 illustrates what should be the cost of the piping system to ensure a given SPB (20, 30, or 40 years). The curve related to the actual SPB corresponds to the results given in Figure 5 and can be used to have an idea on the piping system cost reduction needed to achieve the respective SPB. For example, for approximately 280 to 560 homes, the cost of piping associated to each home must be reduced from about $15,000 to about $8,500 for a 40 years SPB.

CONCLUSIONS

This paper presented an approach to investigate the economic feasibility of residential district energy. A hypothetical home and neighborhood layout were used to generate results from simulations of the model developed. The results show that the system is not economically attractive due to the high capital cost of the piping system used to distribute the chilled and hot water to the air handler units located in each home. Although not considered in this study, the feasibility of residential energy system can be improved by considering socioeconomic benefits such as emission reduction. On the other
hand, the inclusion of a diversity factor can reduce the size of the central utility plant and improve its overall efficiency. In this paper renewable energy systems were not considered. However, these systems should be included when possible to justify the district energy systems because they further increase the environmental benefits.

**NOMENCLATURE**

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<th>Subscript</th>
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**REFERENCES**


