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PUBLIC DATA SOURCES AND MODELING OF DISTRICT HEATING IN THE UNITED STATES

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ABSTRACT

A methodology for computerized modelling of hot water district heating service in any urban area in the United States is described. It is distinguished by the depth and breadth of its data bases, the ease with which any urban market can be analyzed and the wide variety of intermediate information which is obtained.

Real housing and employment data, canvassed for the entire nation and made available on a very small area basis, are conjoined with local climate profiles, labor costs, land use intensity factors, fuel prices and fuel use profiles to generate profiles of heating demands and markets for district heat. This characterization of residential and commercial space and water heating demands permits a system design and costing of piping systems for distribution of hot water, subject to any penetration constraints imposed. A minimal number of assumptions are needed to generate these products from the data bases, many of which were generated in the public domain for other purposes.

INTRODUCTION

District heating has proven to be a practical and economically viable technology for space and hot-water heat service via centralized supply of heat. The rapid escalation of world oil prices in recent years has accelerated growth of this technology in Europe in cognizance of its fuel conservation potential, particularly when district heat is obtained from secondary heat sources, such as power plants, industrial processes, geothermal resources, or refuse incineration.

A number of studies have been done [1, 2, 3] in the United States regarding the economic feasibility of hot water district heating service to residential and commercial customers. In all cases the results are favorable, but these analyses are too few or too sketchy to be of significant value as a foundation for a national district heating policy.

When viewed from the national perspective there are two distinct aspects to district heating service: availability of the necessary technology and its implementation. Reliable hardware has been developed by practitioners in Europe and much of this experience could be put to use in the U.S. However, to what extent district heating could be implemented, where it would provide the greatest benefit, and what it might cost can only be answered by detailed analysis of the many possible markets. It is for this purpose that the analytic methodology described here was developed.

There are five stages in our analysis. The first consists of constructing demand estimates, on a small area basis, and decomposing that market into customer classes by fuel type and heating equipment type. Next, several of these small areas are aggregated, subject to certain criteria, to form a heating zone which becomes the fundamental unit for pipe system design. Pipe systems are designed, that is diameters and lengths are assigned for each zone predicated on peak demands for a variety of penetration scenarios. Heating zones are then interconnected by a subtransmission network and the pipeline is costed. Heat source allocation is determined next via a marginal cost analysis between baseload, cycling, storage, and peaking sources. The last stage consists of cost analyses. These stages are described in greater detail below.

HEATING MARKET CHARACTERIZATION

Among the major difficulties in the United States for influencing levels and patterns of energy consumption through federal policy is the wide diversity in energy supply and demand characteristics exhibited among and within the various regions of the country. This is particularly apparent when the feasibility of a centralized alternative technology such as district heating is under consideration. For such a technology its competitiveness depends strongly on specific market characteristics.

To develop knowledge of supply and demand characteristics for all urban areas, in a systematic and uniform manner, is especially important for district heating assessment. In a free market where customers exercise choice of energy supply form, the price of district heat is certainly a factor in the decision to switch from conventional fuels. In the U.S. at present, the price of natural gas is so low that no alternative technologies can compete on a price basis alone. Other factors such as the age of the housing stock and the type of existing heating system may enter the decision on whether retrofit is a feasible option. Finally, the shared cost of the piping system depends inversely on the number of customers, so the cost of district heat depends strongly on annual heat sales.

Our demand estimates and market characterizations draw from the data obtained in the 1970 Census of Housing and Population [4]. The basic geographic unit in our analysis is the Standard Metropolitan Statistical Area (SMSA). Data for SMSA's is published by census tracts, which are designed to contain about 5000 persons on average. There are 243 SMSA's, and they contain approximately three fourths of the U.S. population. Data for the remainder of the population is published by Minor Civil Division (MCD).

Virtually complete coverage of the population is obtained for housing type, rooms per dwelling unit and persons per dwelling unit. Partial samples are taken of building age and size, fuel type, heating equipment type, certain appliances, water supply, and type of sewage disposal. Unfortunately it has been found by the Census Bureau to be too difficult and unreliable to canvass fuel consumption, so it is necessary for us to use assumed heating demand coefficients which describe the heat put into room air or domestic water, on an annual basis, as a function of climate, dwelling type and size, level of insulation, and family size. Annual residential demand per tract or MCD is gotten simply by adding dwelling unit demands.

Fuel and heating equipment information is not presented in a way which characterizes the market as to the particular heating equipment and fuel used in each type of residential building. This form of classification is needed when designing penetration scenarios since it readily lends itself to imposition of constraints based

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upon building retrofit costs, present fuel type and cost, or customer class. Thus the census data was restructured by a self-consistent cross classification procedure [5] to obtain this format.

Weather data averaged over the 30 year period 1941-1970 have been supplied on computer tape by the U.S. National Oceanographic and Atmospheric Administration. These are used in estimating both annual and peak winter heat demands and are published in summary form in [6]. Regional levels of building insulation have been surveyed by the National Association of Home Builders Research Foundation [7], although this is only specific to the nine U.S. Census Regions. Heating system efficiencies are documented in a number of technical studies funded by the Dept. of Energy. For projection of residential heat demands to future years, population and household forecasts for all tracts and MCD's have been purchased from a private corporation.

The Census Bureau has not done a canvass of commercial buildings, so that an alternate approach had to be devised to make relevant demand estimates on a tract or MCD basis. Estimates of commercial floor space have been made for the Bureau of Economic Analysis [8]; however data are presented on a regional basis, in many cases grosser then the SMSA. Two approaches to disaggregation of this data are taken which yield upper and lower bound estimates of annual commercial heating demand per tract or MCD.

The first step in the disaggregation procedure is to distribute floor space by county and within cities. For certain categories of floor space (profit making enterprises) this can be done by using sales activity data published by the Census Bureau [9], assuming a linear relation between sales activity and floor space inventory. The remaining categories of commercial floor space (non-profit enterprises), including schools, other governmental operations, hospitals, religious and cultural, tend to be distributed more nearly with population, though not perfectly. The necessity to deal differently with these two classes of commercial floor space introduces an element of uncertainty into the analysis and explains why we seek bounds on estimates. Further disaggregation into census tracts also requires separate treatment of the two classes. We must distinguish tracts which lie within the central business district (CBD) since a disproportionate share of profit commercial activity occurs herein.

To allocate profit commercial floor space among tracts in the CBD we assume floor space to be proportional to employment in the CBD. Employment data can be gotten from the Census [4] and a self consistent analysis performed to ensure correct allocation of floor space inside and outside the CBD. To allocate profit commercial floor space among non-CBD tracts requires the use of auxiliary assumptions about its correlation to population. These assumptions can be based upon Census data [4] for commutation distance to work. Allocation of non-profit commercial floor space inside or outside the CBD is more difficult because the Census data does not provide any handles upon which to tie assumptions. Lower and upper bound estimates for CBD tracts, and the converse for non CBD tracts, can be obtained by assuming distribution by resident population and by employment respectively. We assume that fuel type and heating equipment type inventories in the commercial sector are the same as for the residential sector.

Adding commercial demands to the residential demands yields upper and lower bound estimates for heating demands for each tract or MCD. Peak power demand is obtained by dividing the annual demand by annual heating degree days and multiplying by a suitable extreme design temperature difference, based upon the ASHRAE 97.5 percent coldest temperature [10].

Since our data base is computerized, it is easy to modify demands, subject to penetration constraints, by simply eliminating designated customer classes from the summation. Several scenarios of interest are described later.

HEATING ZONES

Several criteria are employed to ensure similarity among tracts which are aggregated to form a heating zone. The most important constraint is that the tracts be contiguous. Density of heat demand, extent of building retrofit, land use intensity, and fuel mix are also considered.

In each SMSA the tracts are ranked in order of density of heat demand, gotten by dividing annual heat demand by tract area. Starting at the tract with greatest density, contiguous tracts are those whose distance between population centroids is least. The tracts are compared in terms of the other criteria and those most compatible are assembled into a heating zone. Zones are not allowed to be arbitrarily large but are held to a total area not exceeding 5 KM^2. Once put into a heating zone, tracts are removed from the tract list and the process repeated until all tracts are assigned to a heating zone. We are able to distinguish CBD and non-CBD tracts in the computer and this characteristic is employed in the aggregation process.

Once a heating zone is formed, it becomes the fundamental unit for pipe system design, and the constituent tract properties are averaged to yield heating zone characteristics.

PIPE SYSTEM DESIGN

Zones are kept small for several reasons. Smallness ensures a high degree of uniformity among constituent tracts. Actual implementation of district heating service would be done on a small area basis, beginning with those zones which yield the greatest payoff. Smallness ensures that pipe diameters are kept small and system layout is compact so that initial capital requirements are held down.

For simplicity, heating zones are assumed to be square, and the computer designs the pipe system from the extremes toward the center in a simple rectangular layout. Optimized diameters and flow rates are calculated for each heating zone using parameterized supply and return temperatures. Conductive losses and pumping power are accounted for at each step of the design. The total number and length of blocks in each heating zone is assigned from a data base established from statistical correlations between street density and land use intensity in a cross section of U.S. cities. Demand is allocated uniformly among blocks. Peak power requirement serves as the design point. The simplifying rectangular shape assumption would affects cost only weakly through inaccurate diameter estimates, but stringent control is placed on pipe length estimates which have a stronger influence on cost.

At present interconnection of heating zones by the subtransmission network is done by hand, but we anticipate that this calculation can be computerized.

Costing is done on a zone by zone basis so that cost to benefit ratios may be used to rank zones in order of payoff. We employ a reference installation cost as a function of diameter for placement of pipes in existing streets in very low density suburban type areas. The labor component of this reference case is scaled by an appropriate factor which reflects complexity of installation due to land use intensity and existing utility services. These factors were established from studies of the statistical relations between installation costs of water and gas mains and land use intensity in a cross section of cities. Finally, local labor and material scale factors relative to reference costs are applied to accommodate the variation in wage rates and material delivery costs from city to city. These factors can be obtained from readily available literature [11].

The design analysis yields a matrix of length requirements by discrete pipe diameters for each zone, and from this the heating zone pipe system installation cost may be easily obtained.

HEAT SOURCE ALLOCATION

Much of the development work reported here has been done under a program of assessment of the potential for geothermal district heating in the United States which is funded by the U.S. Department of Energy, Office of Resource Applications. Therefore our heat source allocation analysis focuses on direct utilization of geothermal energy for base load and stored geothermal heat for cycling load service, with peaking power provided by fossil fired boilers.

A curve of probability density for heat demand as a function of time (commonly called an hourly load curve) is constructed for each market from 30 year average daily temperature data recorded by the local weather station [12].

The known geothermal resources are correlated to urban markets to ascertain transmission distances, and an adopted version of the well development analysis described by Milora and Tester [13] characterizes the cost of developing a geothermal field for heating applications.

A sufficient amount of short term storage capacity is included to smooth out disparity between instantaneous supply and demand. Finally, heat source allocation is made via a marginal cost analysis which compares the incremental cost of adding one geothermal well and increasing the transmission line capacity and storage capacity concomitantly to the cost of supplying the increment of heat, as determined by the demand load curve, via a fossil-fired boiler. This analysis yields the optimum power demand level for the peaking source. The area under the load curve below this peaking level yields the average annual heat delivered from the geothermal resource. The average heat production cost is obtained as a weighted average of the costs for resource produced heat and boiler produced heat.

An analogous procedure would be used were power plants to be considered as heat sources. In this case the marginal cost analysis would yield the optimum service temperature and power level for base load and cycling service. In our geothermal applications we allow the resource temperature to act as a surrogate for this optimum service temperature.

COST ANALYSES

The cost to retrofit buildings is used as a parameter in designing penetration scenarios. Case studies of retrofit requirements are used to develop a data base which is applied to heating equipment classes to estimate the retrofit bill in each tract. This is feasible because the number of potential customers can be estimated from the market characterization analysis. Supplementary information on operating and maintenance costs of conventional heating systems is incorporated in this analysis. Residential and commercial prices for natural gas and #2 fuel oil come from the U.S. Department of Labor [14] and the U.S. Department of Energy. Electricity rates for dwellings with and without electric space heating come from the Federal Power Commission [15, 16]. Data, again, are regional or county specific.

The scenarios under investigation at present are: complete market penetration, market penetration constrained by fuel and/or equipment type, and penetration constrained by those buildings which could economically convert to district heat given current or projected prices for conventional fuels. In the latter case it is necessary to make comparative cost calculations, with district heat and with existing heating system, for the various building classifications (identified by level of heat demand, existing equipment type, and fuel type). To do this it is necessary to assume a delivered cost of hot water to buildings, so a range of demands for district heat are generated as a function of delivered heat cost. Optimum system size can then be gotten by iterating between a set of demand estimates and the costing models for the heat supply and delivery until the cost of delivered heat from the heat supply and delivery models matches the heat cost assumed for a particular set of district heat demands. These calculations can also be structured as a linear programming problem to simplify the analysis. The comparative costing approach is particularly useful because it permits estimation of optimum system size (minimum average cost) as a function of conventional fuel prices, retrofit costs, the level of taxes on district heat, and the price structure of district heat across various customer classes. From these cost analyses one obtains system cost and its components, heat sales, and service levels.

CONCLUSIONS

The methodology we have described here has several attractive advantages. Analysis of an entire urban area can be done very quickly. The methods and analytical framework are quite general and may be readily adapted if new or better data become available, for example, that of the 1980 Census. A minimal number of assumptions are employed, and the methodology is universally applicable. It can thus furnish a systematic analysis of the district heating potential under a variety of scenarios for the entire country, any region, or subregion. Market penetration scenarios and time series implementation of a system under escalating prices of conventional fuels can be handled in a systematic way. The impact of technological developments within any subsystem of the district heating system can be readily evaluated. A great variety of useful products can be gleaned from these analyses and applied to other programs. In particular, the detailed picture of conventional heating systems and levels of demand are quite useful in assessing the impact of other conservation strategies.

The principal limiting factor in this program is the level of aggregation at which the Census Bureau publishes housing and population information. Thus the census tract is the smallest area unit for which the broad spectrum of information relevant to this program is publicly available. Our program is not amenable to detailed engineering design analysis, but the conceptual designs which it can furnish are a time and money saver in regard to laying the groundwork for such projects.

We are limited, at present, to validation of demand estimates for the nation as a whole and for multi-state regions. It is our hope that this work will instigate detailed study of fuel consumption in several cities to provide a better basis for comparison.

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