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THE OPERATION OF SMALL COGENERATION PLANTS AND SHORT-TERM STORAGE FOR DISTRICT HEATING AND PUBLIC ELECTRIC POWER.

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ABSTRACT

The introduction of small cogeneration plants together with the establishment of more complex rate structure for electricity and natural gas have contributed to a renewed interest in short-term heat storage. Studies have, therefore, been initiated in order to determine optimal operational strategies for the new plants and the stores subjected to the new conditions. The results of a simulation study that has been aimed at revealing some of the basic relationships are reported.

INTRODUCTION

In Denmark, cogeneration is responsible for covering a major fraction (27%) of the demand for space heating. Most of the cogeneration is concentrated in a small number of larger cities or towns. This, combined with a desire to increase the use of domestic fuels, such as straw, wood chips, sewage, garbage, manure, and even natural gas, has led to the establishment of a national 450 MW installed electric-power small cogeneration-plant program. The first phase of the program up to about 100 MW, is intended to be semi-experimental. The small number of units contemplated and possible unsuccessful experiments may make some of the plants unprofitable. However, the establishment of these plants, will contribute to the solution of a number of problems such as the balance of trade, the garbage disposal problem, the burning of straw in the fields, and the air pollution. It may even benefit the Danish industry by effectively supporting the development of these new plants through consumer-paid electricity.

A significant number of studies of small cogeneration plants have been undertaken [1] and a limited number of cogeneration plants has been established during the past 15 years. When operating these in the electric system with a two-step price schedule for the electricity and a constant fuel price or when only considering energy versus capital costs, short-term heat storage has turned out to be economically advantageous. It should be emphasized, in this connection, that the operation of a heat store by itself is an expense-generating activity and that it is only through its consequences for the operation of the associated cogeneration plants that the operation of a heat store will lead to economic gains or energy savings.

The new cogeneration plants will be introduced into systems with a three-step price schedule on the electricity and a natural-gas price that depends on the ratio of heat and electricity generated according to a relatively simple formula, given later in this paper. The rest of this paper addresses only natural gas fired cogeneration plants. The most advantageous management strategy for these plants is not known and the optimum dimension of the associated heat stores, when subjected to these new rate structures is not known. But the picture certainly is expected to be significantly more complex than with the old conditions. The results of one study has recently been published that have had similar aims [2], but with emphasis on the optimum dimensions of the cogeneration plant. The present study will emphasize the size and operation of the associated store. The paper will first describe the old situation and the consequent operational philosophy. A simulation model is described and the results of simulation runs are presented and are discussed.

THE PAST

The first cogeneration plants were constructed before there was any established rate structure to account for the possible inconvenience that their existence imposed on the rest of the system. This inconvenience could occur in cases where a cogeneration plant, due to the heat demand, forced other power stations to close down during periods of low demand for electricity at night during winter.

By establishing a two-step price schedule it was possible to reduce this inconvenience, but it might also have reduced the cogeneration share of space heating. The typical two-step schedule specified a limited period, typically eight hours, during summer days, a longer period during fall and spring, and the entire twenty four hours during winters, during which peak-load price was being paid for electricity. During the off-peak periods, a lower price, barely covering the fuel costs was being paid. The optimal cogeneration plant operation was then eight hours during the summer time. With a heat store covering sixteen hours of summer heat demand (or eight hours of excess generating capacity over and above the lowest summer demand), it was possible to build the plant three times as large as what was needed to cover the summer heat demand. Thus, it was also possible to take advantage of the peak-load price during fall and spring.

The two-step price schedule thus represented an attempt to distribute the cost according to the required investment in installed generation capacity and the cost of fuel.

SIMULATION MODEL

The present study is using a simulation model that has been developed by the Danish Energy Agency. This model is used to simulate the generation of heat and electric power for a given cogeneration plant and store size.

The operation is governed by the weekly and annual variations in heat demand and subjected to weekly cyclical conditions of the state of the store. By running a large number of simulation studies it is possible to arrive at an optimal store dimension and associated operational strategy.

The model is based on a number of simplified descriptions, price relations and assumptions. These will now be presented.

The heat demand over a week is assumed constant. The variation of this demand over the year is shown in Figure 1.

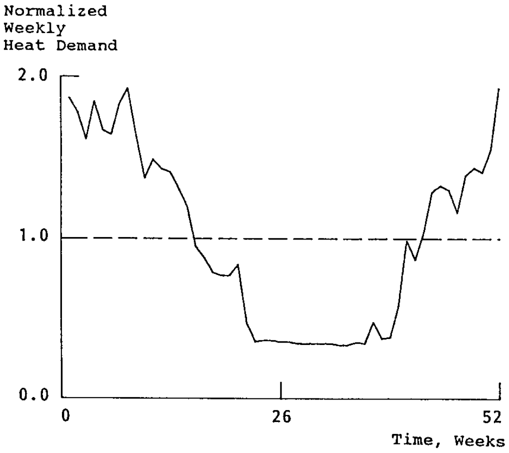

Figure 1. The Week Averaged Heat Demand through the Year.

The cogeneration plants studied are assumed to have a constant ratio between electric power and heat generated.
Three values have been chosen to reflect the characteristics of a fairly large spectrum of potential plants.

With $C_m = \frac{\text{Electric Power}}{\text{Heat Generated}} = \frac{P}{\dot{Q}_G} = 0.235$
we simulate a small gas turbine or back-pressure steam turbine.
$C_m = 0.47$ is typical for a larger gas turbine or back-pressure steam turbine.
$C_m = 0.94$ is a reasonable value for a high-efficiency gas engine.

The costs of establishing the power plants are taken from a catalogue accumulated by the Danish Energy Agency [3]. The pay rates of electric power and natural gas have been developed by the Danish Energy Agency, the Gas Companies, and the Electric Power Companies. [4, 5].

The installation costs of the power plants follow relationships of the type

$$\text{Cost} = A_1 + P \cdot A_2$$

The cost of the water tank is given by

$$\text{Cost} = A_3 Q_L + A_4 \sqrt{Q_L}$$

where A_1, A_2, A_3 and A_4 are constants chosen to fit the experimental data and Q_L is the store size.

The unit price of the natural gas is given by

$$\text{Unit Price} = A_5 \dot{Q}_G + A_6 P$$

where the price for natural gas contributing to the generation of electric power is less than one quarter of that contributing to heating.
The investment costs are written off over a period of 20 years with an annuity of 9 percent.

The price for electric power follows a three-step schedule, depending on the hour of the week as shown in Figure 2.

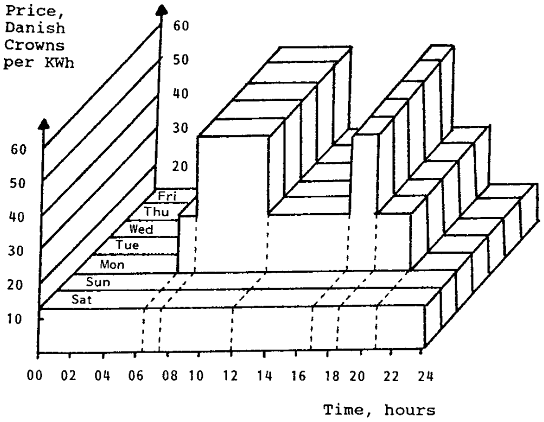

Figure 2. Three-Step Price Schedule for Electricity. The Aftenoon Peak Exists only During Winter Months (November-February).

Stochastic variations of demand have not been considered.

The operation of the store is subjected to two limiting conditions.

1. The store is operated cyclically and is empty at six o'clock on Monday morning.

2. The store has no overload capacity.

The simulation model is based on a simple step - by - step computation in time. The demand for a given geographical area is met by a combination of heat generated from the cogeneration plant and a gas-fired heating plant. The heat is primarily supplied by the cogeneration plant. Deficiencies are supplied by the heating plant. Start or stop costs have not been included.
Simulations have been carried out for specified plant sizes. For each plant size, the store has been varied until the optimum size has been found.

RESULTS OF THE OPTIMIZATION STUDIES.

Store size

Typical curves for the marginal costs of the water tank and the marginal income from the sale of electricity for a given plant size and heat demand are shown in Figure 3. Patterns, generalizations or interpretations of the results have not been obvious. In order to ease the understanding of the results and their significance, the discussion below will start with some general considerations. On this background, the data may more easily be interpreted.

It has to be kept in mind that the curves of Figure 3 give the marginal costs. This means that for example, for $C_m = 0.24$ a small store will not be profitable. Even though the marginal benefits exceed the marginal costs over a significant range of store sizes, the total cost will not be recouped. The reason for this is that the electric power generation is too small to offset the increased cost. However, for $C_m = 0.94$, the marginal benefits exceed the marginal cost for the whole range values up to very large store sizes. On the one hand, this gives a significant return on the investment. On the other hand, this return could be wiped out by fairly small relative shifts in prices of fuel, investments or electricity for store sizes above 60 MWh.

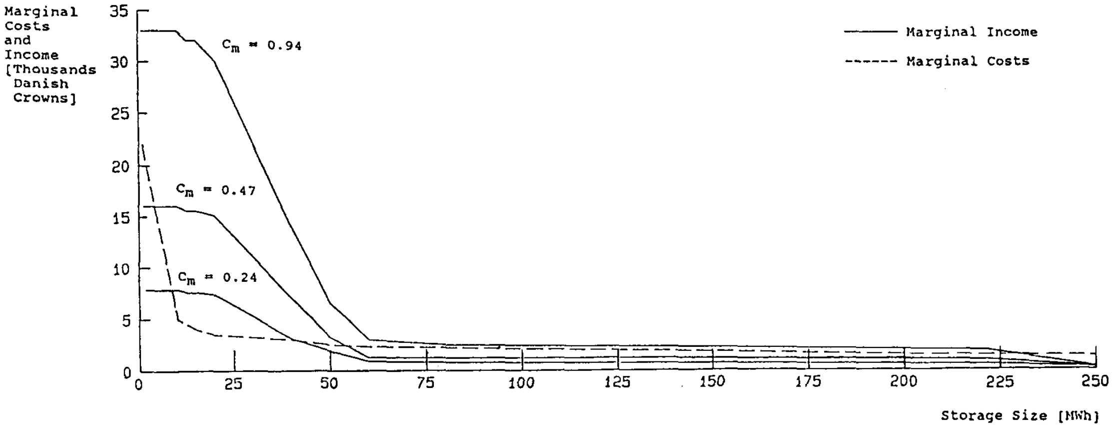

Figure 3. Marginal Cost and Marginal Income Associated with the Establishment of Warm-Water Storage in a District Heating System.
Annual Heat Demand 440 TJ, Cogeneration Heat Capacity 10.6 MJ/s.

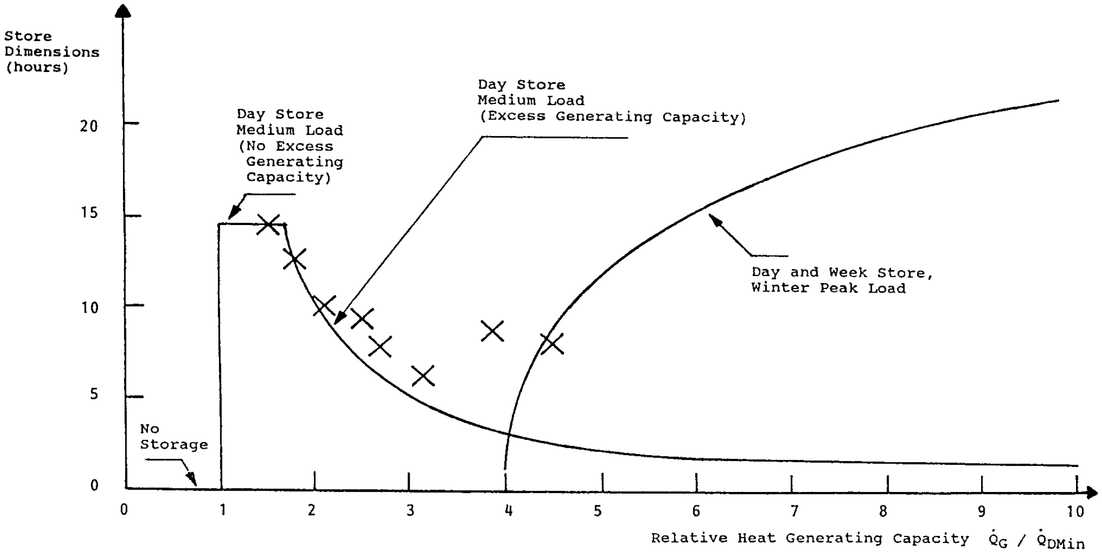

Figure 4. Economical Optimal Storage Dimensions. Result from Simulations (X) and from the Qualitative Reasoning Presented in the Text (solid lines) for

$$C_m \equiv \frac{\text{Electric Power}}{\text{Heat Rate}} = \frac{P}{\dot{Q}_G} = 0.47$$

Past experience has shown that the heat demand during the low-load summer weeks $\dot{Q}_{DMin}$ weigh very heavily in the present context. The energy content of the store is, therefore, expressed by the hours τ that it takes to charge it by the summer excess heat generating capacity $\dot{Q}_G - \dot{Q}_{DMin}$.

Analysis of the detailed output data, indicate that it might be helpful to consider two different store dimensions.

First, there is the day store. For small cogeneration outputs, the main objective of the daily storage cycle would be to generate as much heat and associated electricity as possible during the peak-load and medium-load periods. For cogeneration plants where $\dot{Q}_G$ is smaller than $\dot{Q}_{DMin}$, no store is required. However when $\dot{Q}_G$ increases beyond $\dot{Q}_{DMin}$ a store of a size corresponding to 14,5 hours of excess heat-generating capacity is required as shown by the horizontal line in Figure 4.

When the heat generating capacity of the plant exceeds what is needed to generate the daily heat demand during the 14,5 hours, the store size remains constant, measured in energy units. But since the generating capacity increases, its size decreases when expressed by the number of hours required to charge it, as shown by the falling line in Figure 4.

Second, there is the week store. The main objective of the weekly storage cycle is to provide heat during the weekend.

When the heat generating capacity is increased beyond what is required to meet the daily demand, the excess heat may be accumulated over the five week days to be used during the weekend. The store required to function both in the daily and in the weekly cycles is shown by the rising curve in Figure 4. The weekly storage cycle is

only of interest when the workday requirements already have been met, that is, when the cogeneration plant exceeds a certain size, as shown in the figure.
This means that, beyond a cogeneration plant size of $\dot{Q} = 4\dot{Q}_{DMin}$, two alternative store sizes may exist. One, small, is dimensioned for daily storage and one, large, is dimensioned for daily <u>and</u> weekly storage.

The exact shape of the curves in Figure 3 can not be derived by such simple considerations, but has to be derived from simulation studies.

The optimal store dimensions for $C_m = 0{,}47$ derived by simulations of the type that have lead to data of the type shown in Figure 3 have been included in Figure 4, which, in effect are the main results of the present simulation studies. It is seen that the simulation results are reasonably close to the general curves that have been derived by qualitative arguments, thus confirming these.

The divergence from these curves may be caused by the simplifying arguments that either start from summer medium-load and peak-load periods or from winter peak-load periods. The real situation, reflected in the complete load-duration curve, is more complex, however, and the results of the simulations will also reflect the influence of situations during the year that lie between these two extreme situations.

One complicating factor in applying the results is, as already mentioned, the fact that beyond $\dot{Q}_G = 4\ \dot{Q}_{DMin}$ there are actually two alternatives:
one small day store
or
a quite large day-and-week store.
The arguments leading to these two alternatives were mainly based on energy-systems considerations rather than on economics. There should be no doubt that daily storage is more interesting economically than weekly storage. But the marginal costs of establishing a warm water tank decrease considerably with size, and beyond a certain size the economic gains achieved by exploiting this weekly cycle may be considerable.
However, the required store size may be 5 to 10 times as large as what is required for daily storage. The problem may then be environmental rather than economic. A water tank for day storage is large compared to the corresponding cogeneration plant. A water tank for weekend storage would have overwhelming dimensions, and might not be acceptable in a small community or residential area.

It also has to be kept in mind that the cost of a heat store and also the possible economic gains are about one order of magnitude lower than the cost of the corresponding cogeneration plant and that the potential gains may be wiped out by reasonably modest relative shifts in the prices of fuel, electricity, and water tanks.

The above discussion has only addressed the data for $C_m = 0.47$. As already stated, the data for $C_m = 0.24$ are fairly uninteresting for the modest sizes studied in the present paper, as they show that electric power generation is too small to really matter, and the investment in a storage tank is not very economic.
The data for $C_m = 0.94$ essentially show that in this case the electric power generation is very important. This manifests itself by the fact that week storage becomes interesting even at fairly small values of cogeneration heat. This, in fact means, that it is economically attractive

to generate heat for weekend storage even during medium-load periods (as opposed to day storage).

Operational Philosophy

With a two-step price schedule, the operational philosophy was reasonably simple. With the new three-step schedule, the operation is only slightly more complex. The goal is first to shift as much of the electric power generation as possible to peak-load periods. If there is still uncompensated heat demand this production should be shifted to medium-load periods. The price of electricity in medium-load periods is still high, while the price in low-load periods barely compensates for the cost of fuel. Heat for week storage may be generated during medium-load periods (C_m is high) or only during peak load periods (C_m is moderate) (or not at all C_m is low).

SUMMARY AND CONCLUSIONS

A theoretical investigation of the economics of cogeneration supplemented by warm-water storage subjected to a three-step price schedule for electricity, has been carried out. Some general guidelines may be derived, but no simple design rules, such as the ones described for the old situation with a two-step schedule, seem to govern the design of such plants when subjected to the new conditions. Full-fledged simulations will have to be carried out in order to arrive at sufficiently accurate optimal store dimensions and operational strategy. The results from simulation studies, that give the store as a function of cogeneration plant size relative to the total heat demand in the geographical region supplied by the plant are shown in Figure 4.

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