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OPTIMIZATION OF BIVALENT HEATING SYSTEMS CONSIDERING TIME-OF-USE TARIFFS FOR ELECTRICITY

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Abstract—The cost for producing energy differs a lot due to the load coupled to the distribution grid. In Sweden the load has its maximum during the winter because of the climate. The cost for producing one extra unit of energy is then about 0.50 SEK kWh^{-1} (1 US$ = 6 SEK), while during summer the cost can be ten times lower. In order to encourage the consumers to save energy during the winter when the cost is high, it may be important to introduce a time-of-use tariff, which reflects the cost for producing the energy. Such a rate is present in Malmö, Sweden. When retrofitting buildings it is of course important to consider the applicable rate for energy, in order to decide the optimal retrofit strategy. In the time-of-use rate the peak load is expensive and a heating system that will use less of the peak energy becomes very desirable. A bivalent heating system, where the base load is provided by a heat pump and an oil boiler takes care of the building peak load can sometimes be found to be the best solution. In this paper two different methods are used for the optimization of such a bivalent heating system. One method uses derivative considerations, the OPERA model, while the other uses linear programming.

INTRODUCTION

The cost for energy production differs due to the conditions when the energy is produced. In Sweden, with cold winters, the peak load emerges during the winter. Therefore the cost of producing one extra unit of energy is highest during that season. Due to the marginal cost pricing theory, the total amount of energy produced at that occasion shall have the same price. In the winter the peak load is produced by gas turbines if electricity is considered, while the base load is produced using nuclear and hydro-electrical plants. The energy price for a unit produced using a gas turbine can be higher than 0.50 SEK kWh^{-1} (1 US$ = 6 SEK), while hydro-electrical energy produced during the summer can be less than 0.05 SEK kWh^{-1}. Ordinary tariffs for energy do not reflect this difference in the cost and subsequently, a kWh saved during the summer, for the consumer, will result in the same savings no matter when the energy is conserved. For the energy producing utility however, the time aspect is of great importance. If an energy unit is saved during peak conditions the marginal cost is very high, if lack of capacity is present, the cost can be over 5000 SEK kWh^{-1}, or the cost for building new power plants.

In Sweden, where the nuclear plants are to be phased out, the society has two different options: the production of electricity must be implemented by other power plants, or the energy consumption has to be decreased. An introduction of a time-of-use rate that reflects the cost for the energy production will encourage the desirable behaviour from the consumer. In [1] a more detailed discussion can be found about differential rates and marginal cost pricing.

BIVALENT HEATING SYSTEMS

One way of decreasing the use of expensive peak energy is to install a bivalent heating system. In the system considered here, a heat pump is used for the base load while an oil boiler is used for the peak load. The heat pump will deliver about three units of heat for each unit of electricity. However, the heat pump is very expensive (about 5000 SEK kW^{-1}), and thus it is not possible to use the heat pump as the only heating device. When peak conditions emerge during the winter, an oil boiler is started in order to provide the building with a sufficient amount of heat. The oil boiler however, has a high running cost and it is thus not preferable to use the boiler as the sole heating system. A combination of the two systems appears to be the optimum solution. There are, of course, other heating systems that have to be considered, e.g. district heating, but they are not dealt with here.

CASE STUDY

Since April 1985 a research project has run funded by the Swedish Council for Building Research and the municipality of Malmö, Sweden. The aim of the project has been to elaborate a method that finds the optimal retrofit strategy for each unique building. This method is called the OPERA model, OPtimal Energy Retrofit Advisory, which is described in detail in [2].

In the project a number of buildings have been the subjects for retrofit considerations and in this paper one of the buildings, sited in the block Ansgarius, is dealt with. The building is a rather small multi-family building with 34 apartments in a rather poor thermal condition. The total transmission loss in the building, including ventilation losses is 4.780 kW K^{-1}. The peak load in the building according to the Swedish building code is 167 kW. Running the OPERA model for this building implies that a bivalent system shall be combined with attic floor insulation in order to reach optimal conditions [3]. Ten different heating systems and eight different envelope retrofits have then been considered. In this paper, however, only the bivalent heating system in optimized, the building envelope retrofits are not considered.

Climate conditions

In order to show the optimization process it is necessary to start with the climate conditions in Malmö. In Fig. 1 the monthly mean duration curve is shown. The highest load is found for February (103.7 kW). Note that this is a monthly mean value, the "real" peak load is still 167 kW. The number of hours in February is set to 678 which implies that the energy used is 70 326 kWh. The conditions are also shown in Table 1.

The influence of free energy from persons and applications is neglected here in order to easily show the linear programming method. In the OPERA model this can be studied because of the extensive use of energy balance calculations. This is necessary due to both the heating system and building envelope optimization.

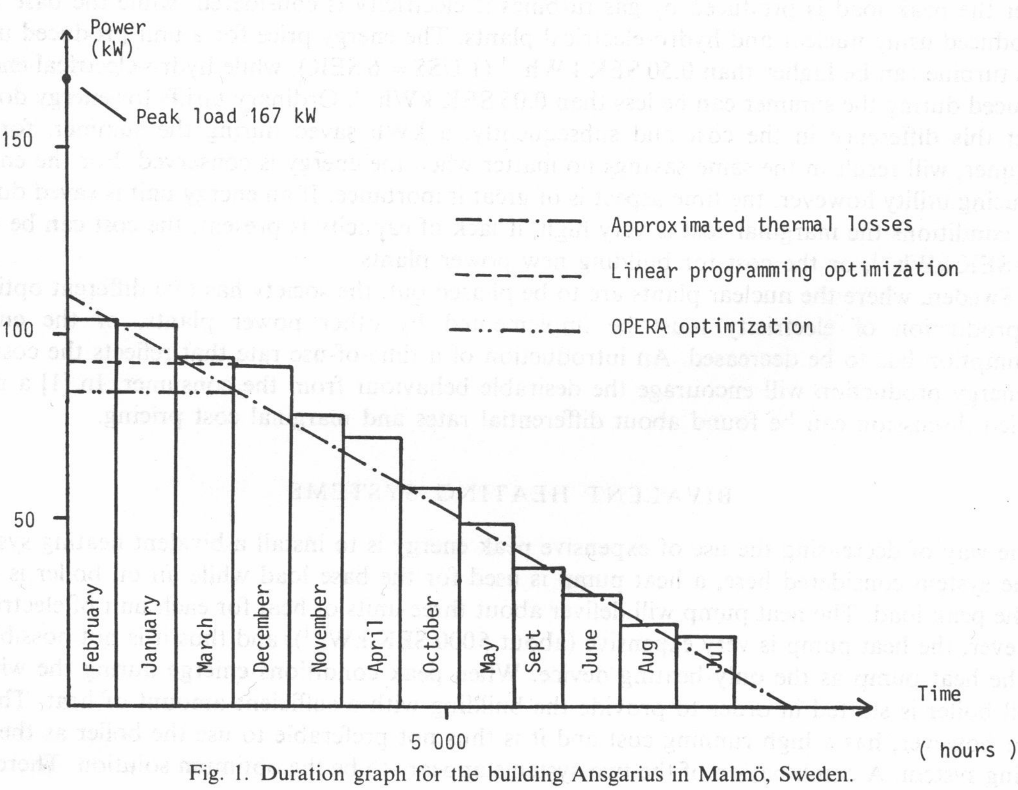

Fig. 1. Duration graph for the building Ansgarius in Malmö, Sweden.

Table 1. Climate conditions in Malmö Sweden considering the building Ansgarius

Month	Load [kW]	Heat loss (kWh]	Month	Load [kW]	Heat loss [kWh]
Jan.	102.8	76460	July	18.2	13514
Feb.	103.7	70326	Aug.	20.6	15292
March	93.7	69704	Sept.	35.9	25812
April	71.7	51624	Oct.	57.8	43031
May	47.8	35563	Nov.	77.0	55409
June	28.7	20650	Dec.	90.8	67570

The electricity tariff

In Malmö a time-of-use rate is introduced as follows:

*Fixed fee	5000 SEK
*Subscription fee	60 SEK kW^{-1}
*Power fee	170 SEK kW^{-1}
*Energy fee:	
Nov.–March; Mon.–Fri., 06.00–22.00	0.392 SEK kWh^{-1}
otherwise	0.252 SEK kWh^{-1}
April, Sept., Oct.; Mon.–Fri., 06.00–22.00	0.252 SEK kWh^{-1}
otherwise	0.222 SEK kWh^{-1}
May–Aug.; Mon.–Fri., 06.00–22.00	0.222 SEK kWh^{-1}
otherwise	0.187 SEK kWh^{-1}

The prices above include taxation of 0.072 SEK kWh^{-1}. It is now possible to calculate the applicable price for each month using the number of high and low price hours. The calculations result in the energy fee:

*Energy fee, Nov–March	0.314 SEK kWh^{-1}
April, Sept. and Oct.	0.236 SEK kWh^{-1}
May–Aug.	0.204 SEK kWh^{-1}.

Normalization

In the OPERA model only continuous functions can be dealt with, i.e. when bivalent systems are to be optimized, and thus these energy prices must be normalized to a fixed price. The normalization means that the utility will achieve the same income for identical thermal loads no matter how the tariff is designed. See [1] for a more thorough discussion about normalization. The procedure is shown below:

$$0.314 \cdot 76460 + 0.314 \cdot 70326 + \cdots + 0.314 \cdot 67570 = 152366.$$

The subscription fee is calculated to be 10039 SEK and the power fee 28446 SEK. The total cost for the energy during one year is thus 190851 SEK. The annual energy loss is 544915 kWh and thus the normalized price will become 0.35 SEK kWh^{-1}.

The OPERA optimization

The costs for the oil boiler and the heat pump, as well as the energy cost from the two devices now have to be calculated. In the OPERA model (and the same is valid for the linear programming system), the optimal solution is found when the total life-cycle cost for the building is as low as possible. The oil boiler cost in this case study is assumed to be $55000 + 60 \cdot P_{oil}$, where P_{oil} shows the thermal power of the oil boiler. The economic life of the boiler is set to 15 years. Further, there is another cost for installation i.e. $200 \cdot P_{oil}$ which has a longer economic life, 50 years, than the boiler itself. Using the present value method the boiler life-cycle cost will become:

$$55000 + 60 \cdot P_{oil} \cdot (1 + 1.05^{-15} + 1.05^{-30} + 1.05^{-45} - \tfrac{2}{3} \cdot 1.05^{-50}) + 200 \cdot P_{oil} \cdot 1 = 55000 + 305.93 \cdot P_{oil}. \quad (1)$$

The same expression for the heat pump has been evaluated as:

$$60\,000 + 8546.34 \cdot P_{hp}. \tag{2}$$

The real discount rate is set to 5% and the project life to 50 years.

In [2] and in [4] it is shown that the energy cost for the oil boiler can be calculated as:

$$(548\,263 - 9\,562 \cdot P_{hp} + 41.7 \cdot P_{hp}^2) \cdot \frac{18.26 \cdot 0.22}{0.75} \tag{3}$$

and the heat pump energy cost as:

$$(9\,562 \cdot P_{hp} - 41.7 \cdot P_{hp}^2) \cdot \frac{18.26 \cdot 0.35}{3.0} \tag{4}$$

The value 548 263 is the total energy need during one year, using the approximation in Fig. 1 due to the least squares method. The present value factor 18.26 emerges from annual recurring costs for 50 years, and 5% real discount rate. The energy prices for the oil boiler and the heat pump are 0.22 and 0.35, respectively, and the efficiency and the *COP* for the heating systems are 0.75 and 3.0. Adding expressions (1) to (4), and noting that $P_{oil} = 167 - P_{hp}$, results in the total life-cycle cost for the building heating system. The expression is minimized by setting the derivative to 0 and the minimum is reached for a heat pump equaling 84 kW.

The linear programming optimization

Another method for optimising the problem above is to use a linear programming method. In this paper it is not possible to make a review of how the method works, but the reader may consult references [5] and [6] for detailed information.

The mathematical problem to minimize, must be expressed in an objective function and in this case the function is:

$$Cost_{hp} + Cost_{ob} + Cost_{energy\,hp} + Cost_{energy\,ob}.$$

The first two parts of the objective function can be found in expression (1) and (2) above, while the energy cost for the heat pump and the oil boiler must be shown for each month and, furthermore using the applicable energy price. The first and last part of the objective function will become:

$$8\,546.34 \cdot P_{hp} + 305.93 \cdot P_{ob} + E_{Jan.} \cdot \frac{18.26 \cdot 0.314}{3.0}$$
$$+ \mathrm{O}_{Jan.} \cdot \frac{18.26 \cdot 0.22}{0.75} + E_{Feb.} \cdot \frac{18.26 \cdot 0.314}{3.0} + \mathrm{O}_{Feb.} \cdot \frac{18.26 \cdot 0.22}{0.75}$$
$$+ \cdots + E_{Dec.} \cdot \frac{18.26 \cdot 0.314}{3.0} + \mathrm{O}_{Dec.} \cdot \frac{18.26 \cdot 0.22}{0.75}.$$

In the expression, $E_{Jan.}$ equals the heat demand from the electrical heat pump during January, and $\mathrm{O}_{Jan.}$ the need for oil during the same month. The constant parts of the objective function are not necessary to encounter because they do not influence the size of the heat pump. There are also some constraints that must be satisfied. Firstly, the energy need for each month must be provided. This is achieved by setting:

$$E_{Jan.} + \mathrm{O}_{Jan.} > 76\,460$$
$$E_{Feb.} + \mathrm{O}_{Feb.} > 70\,326$$
$$E_{March} + \mathrm{O}_{March} > 69\,704$$

and so on for each month during the year, see Table 1. Another constraint that has to be satisfied is that the heat pump power P_{hp} must equal the heat pump energy divided by the number of hours for each month, i.e.:

$$P_{hp} - E_{Jan.} \cdot \tau_{Jan.}^{-1} > 0$$
$$P_{ob} - \mathrm{O}_{Jan.} \cdot \tau_{Jan.}^{-1} > 0.$$

One more constraint is due to the total need for power in the building. The sum of P_{hp} and P_{ob} must exceed 167 kW. The objective function with the constraints above result in a linear program with 26 variables, which has been solved using the LAMPS computer program [7]. The optimal solution found implies that P_{hp} shall equal 91 kW. P_{ob} shall thus equal 76 kW. The heat provided by the heat pump is then 524996 kWh and the oil boiler energy equals 19960 kWh each year, see Fig. 1.

Derivative vs linear programming optimization

The use of linear programming offers a more straightforward method for finding the optimal solution in this case study. The problem can be solved without the approximations which are necessary in the derivative method. The difficulty in linear programming is, instead, to elaborate the problem itself in such a way that it is possible to solve it with commercial computer programs. The case discussed above was rather small but introducing envelope measures and ventilation retrofits will increase considerably the number of variables.

In this case the two methods of optimization did result in a difference in the heat pump size of 7 kW or about 6%, so it will not cause any severe misoptimization if the derivative method is used instead of linear programming (which in this case seems to be the best method to use). It must also be remembered that the use of monthly mean temperatures is an approximation of the real climate conditions. Using diurnal mean values makes the problem more like a continuous function, which implies better performance from the derivative method.

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