Natural gas in optimized bivalent heating systems

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Abstract

In accordance with a referendum, Sweden will abolish nuclear power generation by 2010. To make up for the immediate/substantial scarcity of electric power new fossil fuelled power plants can of cource be constructed. Another way is to reduce the electricity load by converting some of the end use to natural gas which can be obtained from Denmark through a new pipe line to the south of Sweden. We will show how an optimal solution can be found for NG used in a system with both a NG boiler and an electric heat pump. A time-of-use tariff is used to price the electricity and that requires a discrete optimization method. The optimal solution is characterized by the lowest life-cycle cost for the building as an energy system.

INTRODUCTION

When retrofitting a building, the strategy that yields the lowest cost is of vital importance for the owner and time-dependent aspects must be properly accounted for, for instance by using the present-worth method where all costs are transferred to the same base year, see Refs. [1] and [2]. By adding the present worths for the building, installation and operating costs, we obtain the life-cycle cost (LCC). We have developed a technique for evaluating the LCC for a building with retrofits called the OPERA-model (OPtimal Energy Retrofit Advisory). This can be used both for LCC calculations and optimization. However, the model has some constraints, like the fact that all of the measures and their consequences must be expressed in monetary terms. Another limitation is that only energy-related retrofits can be dealt with. The interested reader is referred to Refs. [3] or [4] for details. The model is implemented on large computers such as the CRAY X-MP/48 or NORD 570. The first steps have now been taken for use on smaller computers e.g. IBM AT and others. The municipality of Malmö has made extensive use of the model in their energy-audit service and a number of case studies have recently been presented, see Refs. [5] and [6]. The most important of the general conclusions drawn from studies on the multi-family sector are: (i) A heating system with low operating costs is essential. Such heating systems in Sweden today are district heating systems with short-range marginal cost tariffs, bivalent or dual heating systems with an oil-boiler and a heat pump, or NG fired boilers. (ii) Only a few cheap building-envelope retrofits may profitably be implemented in the building. Attic floor insulation and weatherstripping are normal components of the optimal solution. (iii) A more extensive building retrofit strategy may emerge if the building assets must be renovated for reasons other than energy conservation. (iv) It is important to consider the building as an energy system in order to find the optimal situation. If a multi-family building is to be renovated, the plausible optimal solution is to change the heating system in order to decrease the operating cost and implement attic floor insulation. Some of the interesting heating systems will now be discussed briefly. The district heating tariffs are of the time-of-use (T-O-U) type. Thus, heat is cheaper during the summer and more expensive during the winter. In Malmö, the winter price in 1989 was 0.195 SEK/kWh and the summer price 0.145 SEK/kWh, (1 US $ = 6 SEK). The NG has the still lower price of 0.163 SEK/kWh if a multi-family building is considered. There is another system that must be considered, namely the heat pump, which transforms a part of electricity to about three parts of heat. Unfortunately, it is not possible, because of the high acquisition cost, to install the heat pump for the variable thermal loads. Therefore,a peak heater is introduced, which operates on a more expensive fuel for very short periods. In this bivalent heating system, the heat pump is only used for the base load. Since NG is cheaper than oil, it is desirable to use the NG boiler as a peak-load facility. The heat pump is nearly always operated with electricity, and subsequently the cost of electricity is important. The use of T-O-U rates has become widespread. In Malmö, the high price in 1989 was 0.515 SEK/kWh during peak-load conditions (between November and March, Monday to Friday from 06 am to 10 pm). At other hours the price is 0.245 SEK/kWh. If a heat pump with a COP equal to 3.0 is used, NG will remain cheaper during electricity peak-load conditions. If the heat pump could be used only off peak, the heat price would be about 0.08 SEK/kWh.

THE SWEDISH RETROFIT SUBSIDY SYSTEM

For a building renovation, there are subsidized loans and grants in order to encourage the owner of the building to implement an extensive retrofit strategy. The subsidies may be divided into renovation loans, interest subsidies and energy-retrofit subsidies. Renovation loans are most advantageous and will be used in the examples. It is shown in Ref. [3], using present-worth calculations, that the proprietor will only pay about 50% of the real cost for long-duration retrofits, e.g. attic floor insulation, with the rest paid by society. All costs may be included, building as well as installation costs, as long as the renovation cost does not exceed the cost for a new building. If renovation loans are used, it may be expected that many retrofits will be profitable for the owner of the building. For heat pump compressors which have a short estimated life, the benefits will be reduced. In the following discussion, we will show examples of the influence of subsidies on the retrofit strategy.

CASE STUDY

The OPERA model has been used in Malmö for a number of buildings which are subjects for retrofits. One of these is the block Helleflundran, which is a rather small multi-family building with 17 apartments and a total added apartment area of 1,350 m^2. It is in poor thermal shape with the U-value for the external wall equal to 1.2 W/m^2 K, the windows will have to be changed within 5 years. The existing heating system is an oil-boiler and it is assumed that it is possible to install also electric heating, NG or district heating. There are some 200 input values. The OPERA run yields some interesting retrofit strategies. The use of discrete optimization will be compared with the solution obtained by using OPERA. The existing heating system, i.e. the oil-boiler, has a LCC of 2.10 MSEK (about 350,000 US $) if no building retrofits at all are implemented. If an optimal amount of attic floor insulation is introduced the LCC will decrease with 0.01 MSEK, and if weatherstripping is utilized it will decrease with 0.03 MSEK. These two building retrofits were the only ones found profitable. The resulting LCC will thus be 2.06 MSEK. Two or more retrofits may interact; the use of OPERA yields the appropriate results when this has happened. In this case the expected LCC is exactly the same as the LCC for the combination retrofit calculation or else the difference was so small that it could not be detected. If electric heating is chosen, the interaction can be observed. One more retrofit was selected, i.e. the exhaust air heat pump, but the resulting total LCC is higher than the original value and thus this strategy must be rejected. NG heating, combined with some weatherstripping, results in the lowest LCC, 1.54 MSEK, and represents the optimal solution found by using OPERA. The calculations also showed that a bivalent heating system, here an oil-boiler and a heat pump combined with weatherstripping would be better than solely the oil-boiler, LCC = 1.77 MSEK. Thus, a bivalent heating system with a NG boiler and an electric heat pump might give a lower LCC than the NG boiler alone. It might thus be of interest to examine such a solution. Considering or not the subsidy system, the optimal solution still resulted in a NG heating system plus weatherstripping. If the system was used the strategy also included 0.27 meter (about 12 inches) attic floor insulation. This solution, found optimal by using OPERA will later be compared with a bivalent NG - electric heat pump system.

ENERGY TARIFFS

As mentioned above T-O-U tariffs for energy are implemented in Malmö. The district heating tariff has a season dependent price per kWh. From November to March the price is 0.195 SEK/kWh while it is 0.145 SEK/kWh the rest of the year. The electricity rate is also dependent on the season and further on the time of the day. Weekdays from 6 am to 10 pm, November to March, the price is 0.515 SEK/kWh while 0.245 SEK/kWh is valid other times. The prices include taxation of 0.072 SEK/kWh. NG may be purchased at a rate of 0.163 SEK/kWh. There are also other tariff elements but they are of minor importance in this case. The OPERA model is provided with a special subroutine for energy-balance calculations. The climate is described in terms of monthly mean values for the outside temperature. In order to optimize the retrofit strategy for the building and also take proper account of the T-O-U rates, the cost must be calculated month by month. When the electricity tariff above is considered, the price also differs over the day and in OPERA it is necessary to evaluate monthly mean values of these prices. The electricity rate has therefore been transferred to a tariff found in Table 1.

Month	Price [SEK/kWh]	Month	Price [SEK/kWh]
January	0.373	July	0.245
February	0.374	August	0.245
March	0.379	September	0.245
April	0.245	October	0.245
May	0.245	November	0.377
June	0.245	December	0.367

Table 1: Monthly mean prices calculated from the electricity T-O-U tariff

THE THERMAL DEMAND AND RETROFIT COSTS OF THE BUILDING

The design temperature due to the Swedish building code is - 14 °C (7 °F) in Malmö, the desired inside temperature is set to 21 °C (70 °F) and the total transmission coefficient is 3 274 W/K, including ventilation losses. The thermal peak-load of the building has been calculated to 115 kW. The energy balance routine in OPERA presents the energy losses in the building as 296 000 kWh/year. In Table 2 it is shown how the situation changes when some retrofits found optimal are implemented.

Retrofit measure	Thermal load [kW]	Thermal transm. [kW/K]	Annual energy [MWh]	Retrofit cost [MSEK]	Inevitable retrofit cost [MSEK]
Existing building	115	3.274	296	0.00	0.237
Attic floor ins. 0.27 m	104	2.969	265	0.85	0.237
Weather-stripping	100	2.849	252	1.25	0.237

Table 2: Optimal retrofits and resulting thermal and economic status

When the attic floor was insulated with 0.27 meter of extra insulation the peak-load decreased to 104 kW. However, the retrofit costs some money, viz. 85 000 SEK. The inevitable retrofit cost shows what money must be paid either the building is to be retrofitted or not. In this case, that cost did not change at all, because the attic floor insulation was not supposed to have any inevitable cost, as nothing had to be done to the existing attic from other than energy conservation reasons. The weatherstripping, however, did not generate a higher inevitable cost because the existing caulking was not supposed to have any remaining life. In Ref. [3] there is a thourough discussion about inevitable retrofit costs.

The OPERA model, however, also presents the following table. Note that all the values in Table 3 are present values for a project life of 50 years and a real discount rate of 5 %.

Salvage value existing oil-boiler	0.010
Inevitable retrofit cost	0.237
New boiler cost	0.031
Piping cost	0.010
Energy cost	0.938
Retrofit cost	0.125
Connection fee, natural gas grid	0.012

Table 3: Contents of the LCC in MSEK calculated by the OPERA model

It is obvious that the energy cost must be decreased to reduce the total LCC significantly. This can be done by a bivalent heating system.

BIVALENT SYSTEM OPTIMIZATION

In Refs. [3] and [7], it is shown how a bivalent heating system can be optimized, also considering retrofit measures and free energy from appliances etc. These works assumed that the heat pump electricity was paid according to a fixed rate. In Refs. [8] and [9] T-O-U rates were introduced, which also made it necessary to use a linear programming method for the optimization, if no mean values could be accepted. These later papers did not deal with free energy considerations and furthermore, not with a heat pump turned off during peak-load. This, because of the low electricity price which made it profitable to use the heat pump constantly during the heating season. The optimization process must start by considering the energy balance for the existing building. The OPERA model deals with monthly mean outdoor temperatures and the degree-hours in Table 4 are calculated disregarding any free energy.

The degree-hours are thus generated when the outdoor temperature is lower than the desired inside ditto. It is shown in the table, that only hot water heating is needed in the summer. This implies that if space heating energy is conserved during summer it is of no use to the proprietor. So, this energy is excluded from insulation optimization. During the heating season the free energy is included. Marginally it is unimportant if the energy comes from free gains or from the boiler, as long as it is within the building, see Ref. [10]. The energy situation can also be depicted in a duration graph where the thermal load is shown as a function of time over the year, Fig. 1.

The base load in Fig. 1 is filled with free energy from appliances and solar gains. In June, August and July the free energy exceeds the total losses and thus no space heating is needed. During April, October and May the heat is supplied by the electrical heat pump. For these months the tariff, for electricity, is so low that NG cannot compete. In April the thermal power of the heat pump is not sufficient, and thus NG must be used when the need exceeds the thermal

Month	Degree hours	Energy transm.	Hot water	Free gains	From the boiler	For insulation optimization
January	15 996	52.4	4.2	6.0	50.5	52.4
February	14 713	48.2	4.2	7.7	44.7	48.2
March	14 582	47.7	4.2	11.8	40.2	47.7
April	10 800	35.4	4.2	14.6	24.9	35.4
May	7 440	24.4	4.2	18.5	10.0	24.4
June	4 320	14.1	4.2	19.1	4.2	0.0
July	2 827	9.3	4.2	18.8	4.2	0.0
August	3 199	10.5	4.2	16.6	4.2	0.0
September	5 400	17.7	4.2	13.4	8.5	17.7
October	9 002	29.5	4.2	9.5	24.1	29.5
November	11 592	38.0	4.2	6.4	35.7	38.0
December	14 136	46.3	4.2	5.4	45.0	46.3
Sum	114 008	373.5	50.4	147.8	296.2	339.6

Table 4: Energy balance in MWh/year for Helleflundran in Malmö, Sweden

power of the heat pump. For January, February etc. the tariff implies that NG is to be used because of high electricity prices, and thus part of the heat is supplied with NG while the rest is supplied by the heat pump.The question is how to find the best thermal size of the heat pump for the minimum LCC. In order to examine if a bivalent NG-boiler - electrical heat pump system is of any interest, an OPERA run has been elaborated when the prices for the oil-boiler equipment were changed to those of a NG system. The OPERA model uses derrivative methods for optimization of bivalent systems. Some simplifications are thus made in order to change the originally discrete problem to a continuous ditto. In Fig. 2 the slope of the thermal losses has been approximated by the method of least squares, and the free gains have been displayed as a rectangle containing the proper amount of free heat found in Table 4.

Another approximation, also necessary to implement, is the applicable energy price. In the OPERA model the T-O-U rate is normalized, i.e. the used price yields the same income to the utility. The normalized electricity price, in this case study, has been calculated to 0.36 SEK/kWh. See Ref. [8] for more details about normalization. The result from the OPERA optimization is that the bivalent NG - heat pump system yields the same LCC as the system with only the NG boiler. The retrofits were also the same but the insulation was slightly thicker. The energy cost, 0.707 MSEK, is considerably lower but is almost exactely balanced by a higher heating equipment cost, 0.261 MSEK for a 100 kW NG-boiler and a 22 kW heat pump. It is thus not possible to tell that one system is preferable to the other, but the caculations show that a bivalent system is of interest to consider. If the necessary approximations, made by OPERA, could be overlooked the result might be different. A discrete optimization method must then be used. Ref. [7] shows how a linear program is elaborated in order to find the minimized LCC for a bivalent system, but only the result is presented here. The two different strategies competing for optimal status are presented, first with only a NG-boiler in Table 5, and then a NG - heat pump system in Table 6.

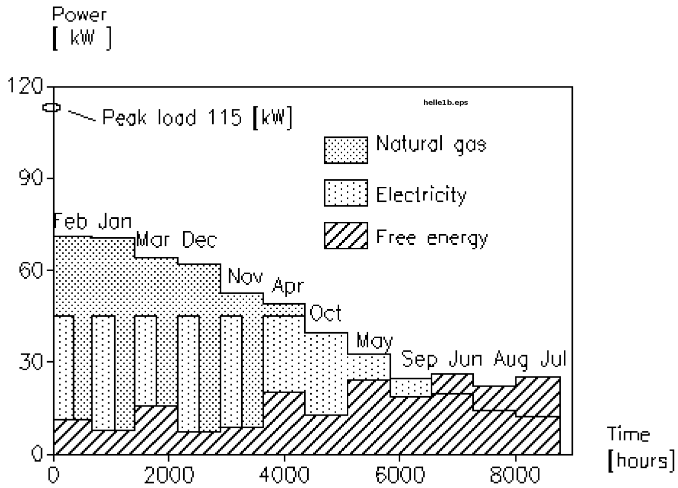

Figure 1: Duration graph used for discrete optimization. Thermal load as a function of time for the existing building Helleflundran in Malmö, Sweden

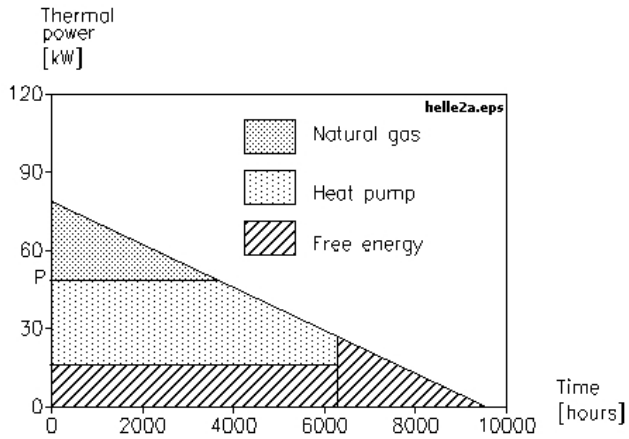

Figure 2: Approximate duration graph used by the OPERA model. Thermal load as a function of time for the existing building Helleflundran in Malmö, Sweden

Salvage value existing oil-boiler	0.010
Inevitable retrofit cost	0.237
Natural-gas boiler, 100 kW	0.031
Piping cost, natural-gas boiler	0.010
Energy cost, 252 MWh, natural-gas	0.938
Retrofit cost, insulation 0.27 m	0.086
Retrofit cost, weatherstripping	0.039
Connection fee, natural gas grid	0.012
Total cost	1.363

Table 5: Contents of the LCC in MSEK calculated by discrete optimization. Naturalgas boiler, attic insulation and weatherstripping

Salvage value existing oil-boiler	0.010
Inevitable retrofit cost	0.237
Natural-gas boiler, 100 kW	0.031
Piping cost, natural-gas boiler	0.010
Heat pump, 10 kW thermal power	0.130
Piping cost, heat pump,	0.001
Energy cost, 194 MWh, natural-gas	0.938
Energy cost, electricity 58 MWh	0.087
Retrofit cost, insulation 0.26 m	0.085
Retrofit cost, weatherstripping	0.039
Connection fee, natural gas grid	0.012
Total cost	1.365

Table 6: Contents of the LCC in MSEK calculated by discrete optimization. Bivalent system, attic insulation and weatherstripping

Note that Table 5 and Table 3 give exactly the same LCC in spite of the different methods for optimization. Table 6 shows that also the discrete method led to a competitive bivalent system, even if it had a slightly higher LCC. Important, however, is that it led to a much smaller heat pump than in the OPERA case. This is mainly due to the electricity T-O-U rate which forced the heat pump to be turned off during peak-load conditions. The fact that the normalized electricity price according to this, were to be lower, which implies that a larger heat pump were to be chosen, did not influence to any substantial degree.

CONCLUSIONS

Our case study shows that NG is of interest for space heating in Sweden today. The LCC did not differ very much if NG was the only heating source, or if it was used as part of a bivalent heating system, with an electric heat pump for the base load. During peak-load as well as during high electric price conditions the NG-boiler was used. The study also shows that, in spite of the almost identical LCC for the two systems, the differential optimization method leads to some misoptimization. The same overall strategy is chosen, but the thermal power of the heat pump is oversized. This depends on the fact that the T-O-U rate is normalized in a derrivative method in order to make the mathematical energy system continuous. If the derrivative method is used and the system found optimal is installed in the building, the profit might not be the expected, because in reality, the system works as a discrete system.

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