VOLUME 15 NUMBER 11 NOVEMBER 1990 ISSN 0360-5442

TECHNOLOGIES · RESOURCES · RESERVES · DEMAND

ENERGY

IMPACT · CONSERVATION · MANAGEMENT · POLICY

The International Journal

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INDEXED IN Curr. Cont. ASCA, Biosis Data., Cam. Sci. Abstr., Chem. Abstr. Serv., Curr. Cont./Eng. Tech. & Applied Sci., CABS, Eng. Ind., Environ. Per. Bibl., INSPEC Data., Curr. Cont. Sci. Cit. Ind., Curr. Cont. SCISEARCH Data.

ISSN 0360-5442
ENEYDS 15(11) 935–1074 (1990)

PERGAMON PRESS

Oxford · New York · Beijing · Frankfurt
São Paulo · Sydney · Tokyo · Toronto

Energy Vol. 15, No. 11, pp. 993–999, 1990
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0360-5442/90 $3.00 + 0.00

NATURAL GAS IN OPTIMIZED BIVALENT HEATING SYSTEMS

STIG-INGE GUSTAFSSON and BJÖRN G. KARLSSON
Institute of Technology, Department of Mechanical Engineering, Energy Systems,
S-581 83 Linköping, Sweden

(*Received 12 October 1989; received for publication 2 April 1990*)

Abstract—In accordance with a public referendum held in 1980, Sweden will phase out nuclear power completely by 2010. One way to compensate for an immediate, appreciable scarcity of electric power is to construct new fossil-fuel power stations. Another is to reduce the burden on electric power by converting some end-user facilities to operate on natural gas (NG) imported from Denmark through a new pipeline to southern Sweden. We show how an optimal solution can be found for NG operation of a system incorporating an NG boiler and an electric heat pump. Electricity is priced by a time-of-use tariff (TOU) requiring a discrete optimization method. The optimal solution is characterized by the lowest life cycle cost (LCC) for the building as an energy system.

INTRODUCTION

When a building is retrofitted, it is to the owner's advantage to find a strategy that yields the lowest LCC. Time-dependent aspects must be properly accounted for by applying, for instance, a present-value method with all costs transferred to the same base year.[1,2] The LCC is obtained by adding installation and operating costs to the present value of the building. We have developed a model for evaluating the LCC of a retrofitted building: the OPERA model (OPtimal Energy Retrofit Advisory). OPERA can be used for LCC calculations and for optimization. However, its use has constraints. One is that all measures and their consequences must be expressed in monetary terms. Another is that only energy-related retrofits can be evaluated. The interested reader is referred to Refs. 3–4 for details. OPERA is implemented on large-scale computers such as a CRAY X-MP/48 or a NORD 570. Initial work has begun on implementations for IBM AT microprocessors and compatibles.

Malmö, Sweden's third largest city, is located opposite Copenhagen and has a population of around 250,000. The local authorities in Malmö have made extensive use of OPERA in the municipal energy-audit service. Several case studies from Malmö's public housing sector were recently presented.[5,6] A number of the general conclusions drawn from these studies are especially significant: (i) it is essential that a heating system has low operating costs. In contemporary Sweden, this usually means one of three system types: district heating systems with short-range, marginal cost tariffs, bivalent or dual heating systems equipped with an oil boiler and heat pump, or NG-fired boilers. (ii) Only a limited number of relatively inexpensive retrofits of building envelopes may be carried out on a structure. An optimal solution normally includes attic-floor insulation and weatherstripping. (iii) A more far-reaching retrofit strategy may emerge when a building is renovated for reasons other than energy conservation. (iv) An optimal solution requires that the building is perceived as an energy system.

When a multifamily building is renovated, an optimal solution for decreasing operating cost might seem to be to change the heating system and insulate the attic. Some of the more interesting heating systems will now be briefly discussed.

District heating tariffs are time-of-use tariffs (TOU) with heat cheaper in the summer and more expensive during the winter. In Malmö in 1989, the summer price of district heat was 0.145 SEK/kWh and the winter price 0.195 SEK/kWh, (US$ 1 = SEK 6). Applying an NG solution in a multifamily building gives the price 0.163 SEK/kWh.

Another widely-used system is the heat pump, which allows us to transform one part of electricity to about three parts of heat. High acquisition cost unfortunately makes it irrational to install a heat pump for variable thermal loads. This deficiency may be remedied by introducing a peak heater that operates on expensive fuel only for brief periods of time. A bivalent heat-pump heating-system is created, in which the heat pump is used only for the base load. Since NG is cheaper than oil, it is appropriate to incorporate an NG-boiler as a peak-load facility.

Most heat pumps are electrically powered, and the cost of electricity is consequently a significant factor. Time-of-use tariffs are widely used in Sweden. In Malmö, the highest 1989 price was 0.515 SEK/kWh during peak load intervals between November and March, Monday–Friday, from 6 a.m. to 10 p.m. The lowest price, applicable for the remainder of this time span, was 0.245 SEK/kWh. When a heat pump with a coefficient of performance (COP) equal to 3.0 is used, NG is still the cheaper alternative during peak load hours. If the heat pump were used only during off-peak hours, the heat price would be about 0.08 SEK/kWh.

SWEDISH SUBSIDY SYSTEM FOR BUILDING IMPROVEMENT

A number of subsidized loans and grants are available for building improvements to encourage housing owners to adopt an extensive retrofit strategy. The subsidies may be conversion loans, interest subsidies, or energy conservation loans. Conversion loans are granted for inner or outer changes to a building which will improve its use or lengthen its life span. This type of loan is the most advantageous and is applied in the following examples. Using calculations based on present values, Ref. 3 shows that the owner will pay only about 50% of the real cost for long-term improvements such as attic-floor insulation. The other half is subsidized by society. All costs may be incorporated, rebuilding as well as installation costs, as long as the conversion cost does not exceed that of an equivalent new building. When conversion loans are applied, it may be expected that many retrofits will become profitable for a building's owner. Benefits are reduced for items with a short life expectancy, such as heat pump compressors. In the following discussion, we will show how subsidies influence the retrofit strategy.

CASE STUDY

The OPERA model has been used in Malmö for a number of buildings subjected to retrofitting work. One is the *Helleflundran* apartment building, a relatively small multifamily house containing 17 apartments with an extended apartment area of 1350 m^2. The building is in poor thermal condition; the external wall heat-transfer coefficient or *U*-value is equal to 1.2 W/m^{2}K. The windows will have to be replaced within 5 yr. The present heating system is an oil boiler, but installation of electric heating, NG or district-heating facilities is presumed to be possible. Some 200 input values are required for the building. Running the OPERA model yields several interesting retrofit strategies. The OPERA solution will be compared to the solution derived through discrete optimization.

The present oil boiler heating system has an LCC of MSEK 2.10, or about MUS$ 0.350 in a scenario without any building retrofits. Insulating an optimal amount of attic floor will decrease the LCC by about MSEK 0.01 and, if weatherstripping is also applied, the overall decrease will be MSEK 0.03. These two building retrofits were the only ones found to be profitable for the owners. The resulting LCC will be MSEK 2.06.

Two or more retrofit measures may interact *and it might in some cases be thought that two individual measures carried out together would save more energy than they actually do.* OPERA allows consideration of the true situation and yields the correct results. In the case at hand, no difference could be detected between the two methods. When electric heating is entered as a parameter, the interaction is noticeable. Still another retrofit operation was introduced: an exhaust-air heat-pump. The result was an LCC greater than the original value so that this particular strategy must be rejected. Natural gas heating combined with weatherstripping gives the lowest LCC, MSEK 1.54; this is *the* optimal solution *from the use of* OPERA. Our calculations also show that a bivalent heating system composed of an oil-boiler and a heat-pump and combined with weatherstripping would perform better than the oil-boiler alone. The LCC in this scenario would be MSEK 1.77. This result leads us to surmize that a bivalent heating system made up of an NG boiler and an electric heat pump might give a lower LCC than the NG boiler alone. This assumption can be tested.

Whether or not the subsidy system is included as a parameter, OPERA finds the optimal solution to be an NG heating system, weatherstripping, and attic-floor insulation about 0.3 m (~12 in.) thick. This solution will later be compared to the result for a bivalent heating system operating on NG and electricity.

ENERGY TARIFFS

As mentioned previously, TOU energy tariffs are used in Malmö. The district-heating tariffs are seasonal. From November to March, the price is SEK/kWh 0.195; during the remainder of the year, it is SEK/kWh 0.145. Electricity rates are SEK/kWh 0.515 and SEK/kWh 0.245, respectively. The electricity prices include an energy tax of SEK/kWh 0.072. There are other price elements included in the tariffs but none has a significant effect on the result. Natural gas is available for SEK/kWh 0.163. The OPERA model has a special subroutine for calculating energy balances. The outdoor climate is defined as the monthly mean values. To optimize the retrofit strategy for the *Helleflundran* apartment building and properly account for the TOU rates, the cost must be calculated month by month. The electricity tariffs also differ according to time-of-day; and OPERA is used to evaluate monthly mean values of these prices. The electricity rate is thus transformed to the tariffs shown in Table 1.

Table 1. Monthly mean prices calculated from the electricity TOU tariff.

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

THERMAL DEMAND AND RETROFIT COST

The design outdoor temperature in Malmö is defined in the Swedish building code as 14°C (57°F); the indoor temperature in the OPERA model is set equal to 21°C (70°F) and the heat-transfer coefficient is consequently 3274 W/K. The thermal peak load of the building is estimated at 115 kW. The OPERA energy-balance routine finds that energy losses in the building will be 296,000 kWh/yr. Table 2 shows how the situation changes when optimal retrofits are introduced. Insulation of the attic floor with an additional 27 cm decreased the peak load to 104 kW. Retrofit costs for this activity were MSEK 0.85. The unavoidable retrofit cost is defined as the retrofit expenditure that is necessary, whether or not the measures save energy, for instance, window frames attacked by rot must be replaced. In the case described, insulation of the attic floor was a purely voluntary energy-saving measure and the unavoidable cost was zero. Weatherstripping the windows was also necessary whether it led to energy savings or not, because the window frames had reached the end of their useful life span. The authors of Ref. 3 give a thorough discussion of unavoidable retrofit costs.

The OPERA MODEL also yields the values in Table 3, which are present values for a projected life span of 50 yr and a real discount rate of 5%.

In order to reduce the LCC significantly, we must decrease the energy cost. This can be done by using a bivalent heating system.

Table 2. Optimal retrofits and resulting thermal and economic status.

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 insulation 0.27 [m]	104	2.969	265	0.85	0.237
Weather-stripping	100	2.849	252	1.25	0.237

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

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
Total cost	1.363

BIVALENT SYSTEM OPTIMIZATION

The authors of Refs. 3–7 show how a bivalent heating system can be optimized through retrofit measures while conserving incidental heat gains from equipment. These scenarios assume a fixed electricity rate for running the heat pump. The authors of Refs. 8–9 introduce TOU, which cannot be clearly shown by a continuous function. It is necessary to apply linear programming to optimize the problem unless average values are acceptable. None of the scenarios reckon with incidental heat gain nor assume that the heat pump was turned off during peak loads. The low electricity price makes it profitable to use the heat pump constantly during the winter season. The optimizing process must start by reviewing the building energy balance. The OPERA model deals with monthly mean outdoor temperatures. The degree-hours in Table 4 ignore incidental heat gains. Degree-hours are obtained when the outdoor temperature drops below the desired indoor temperature. Table 4 shows that, during the summer, heating is

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

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

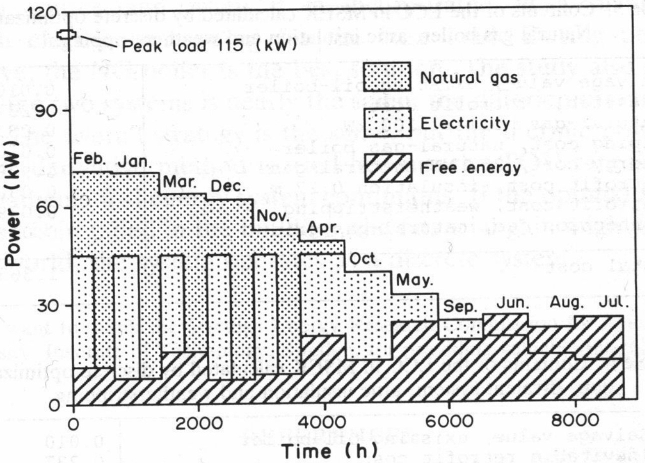

Fig. 1. Duration graph used for discrete optimization. Thermal load as a function of time for the existing building Helleflundran in Malmö, Sweden.

needed only for hot water, therefore, conserving space heating would not be meaningful. This energy is therefore excluded from the calculation when we look for the optimal thickness of the insulation.

Incidental heat gains are included in the calculation for the winter season. Actually it does not matter if the heat comes from incidental gains or from the oil boiler, as long as it is within the building.[10] The energy situation can also be graphically depicted by showing the thermal load as a function of time over 1 yr; see Fig. 1.

Reference to Fig. 1 shows that considerable share of the base load is supplied by solar radiation and incidental heat gains from other equipment. During June, July and August, incidental gains exceed incidental losses, and no space heating is necessary. During April, May and October, heat is supplied by the electrical heat pump also during peak load. During these months, the electricity tariff is so low that the use of NG is not competitive. In April, thermal power from the heat pump will not fill the need and NG must be used. January, February, and March are typical for periods when high tariffs make NG a feasible source for part of the heat, the remainder being supplied by the heat pump. The critical task is finding the thermal size of the heat pump that gives the lowest LCC.

To examine the overall significance of a bivalent NG boiler and electrical heat pump, an OPERA simulation replaced the oil price and oil boiler costs with NG costs. The OPERA model involves the use of derivative methods to optimize bivalent systems. Simplifications are introduced to convert the discrete problem to a continuous one. Figure 2 shows how the incidental heat gains are distributed in the form of a rectangle when the right amount of kWh are applied.

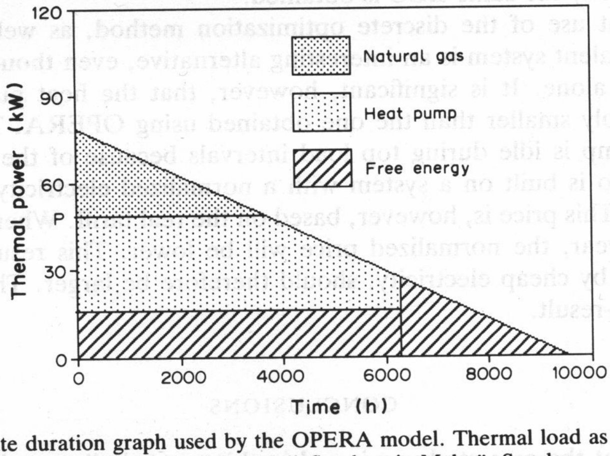

Fig. 2. Approximate duration graph used by the OPERA model. Thermal load as a function of time for the existing building Helleflundran in Malmö, Sweden.

Table 5. Contents of the LCC in MSEK calculated by discrete optimization. Natural gas 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
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 6. Contents of the LCC in MSEK calculated by discrete optimization. Bivalent system, 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, natural-gas 194 MWh	0.723
Energy cost, electricity 58 MWh	0.087
Retrofit cost, attic insulation 0.26 m	0.085
Retrofit cost, weatherstripping	0.039
Connection fee, natural-gas grid	0.012
Total cost	1.365

Another necessary approximation is the energy price for each case. OPERA is used to normalize TOU. In other words, the price used in the calculation will give the same revenue to the public utility. The normalized electricity price in this particular case is calculated to be 0.36 SEK/kWh. The procedure and reasons for normalization are explained in Ref. 8. The OPERA optimization results in the same LCC for the bivalent NG and heat-pump system as for the NG boiler system. The retrofit equipment was the same, but the insulation was thicker than 27 cm. The energy cost of MSEK 0.707, is considerably lower, but this saving is counterbalanced by a higher cost for heating equipment, *namely*, MSEK 0.261 for a 100 kW NG boiler and a 22 kW heat pump. We therefore cannot say with any certainty that one system is better than the other, but calculations indicate that a bivalent system is a strong contender. If we could ignore the approximations made with OPERA, the result might be different. To do so, we must use a discrete optimization method.

Reference 9 shows how the problem can be expressed mathematically: the bivalent system is subjected to linear optimization. Only the result is presented here. Two competing strategies for optimal status are presented. In Table 5 we show the NG boiler solution and in Table 6 the NG and heat-pump solutions. As we see in Tables 5 and 3, despite the different methods used for optimization, exactly the same LCC is obtained.

Table 6 shows that use of the discrete optimization method, as well as that of OPERA, indicates that the bivalent system is an interesting alternative, even though costs are somewhat higher than for NG alone. It is significant, however, that the heat pump suggested for the purpose is considerably smaller than the one obtained using OPERA. This result is obtained because the heat pump is idle during top load intervals because of the high electricity price. The OPERA scenario is built on a system with a normalized electricity price, which was the same all year round. This price is, however, based on the real tariff. When the equipment is idle during parts of the year, the normalized price will be lower. This result would imply that a heat-pump, powered by cheap electricity, should therefore be larger. This fact however could not influence the end-result.

CONCLUSIONS

We have shown that the case study reviewed in this paper indicates that NG is a significant competitor for space heating in contemporary Sweden. The LCC differs only slightly when NG is the sole heating source and when it is incorporated in a bivalent heating system supplemented by an electric heat pump for the base load. During peak loads and when electricity is expensive, the NG boiler is the best solution. The study also shows that, although the LCC for each of the two systems is nearly the same, the differing optimization methods give optimization errors. The overall strategy is the same, but the thermal power of the heat pump is oversized when the derivative method is used because the TOU rate is normalized. This in order to make the mathematical energy system continuous. If the optimal system resulting from the derivative method is installed in the building, the financial gain might be less than expected because, in the real world, the system operates as a discrete system.

Acknowledgements—We want to thank the Swedish Energy Research Commission for funding this project and T. B. Johansson, Lund University, Institute of Technology, Sweden, for providing valuable insights to this study.

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