PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Research at the Building Research Establishment into the Applications of Solar Collectors for Space and Water Heating in Buildings [and Discussion]

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Research at the Building Research Establishment into the applications of solar collectors for space and water heating in buildings

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A completed study of a solar hot water heating system installed in a school showed an annual average efficiency of 15%, the low efficiency largely caused by the unfavourable pattern of use in schools. Field studies, in 80 existing and 12 new houses, of a simple domestic hot water system have been initiated to ascertain the influence of the occupants on the actual performance of solar collector systems. The development of testing methods of solar collectors and solar water heating systems is being undertaken in close collaboration with the B.S.I. and the E.E.C.

Solar space heating is being investigated in two experimental low energy house laboratories, one using conventional solar collectors with interseasonal heat storage and the other a heat pump with an air solar collector. Studies of the cost-effectiveness of solar collector applications to buildings in the U.K. show that they are far less cost-effective than other means of conserving energy in buildings.

INTRODUCTION

The B.R.E. research on water and space heating using solar collectors is part of a broad programme on solar energy use in buildings, which includes the design of buildings to maximize the utilization of solar gains, design to control summertime overheating without using energy for cooling, the application of heat pumps for space and water heating and the optimization of building lighting taking account of daylight. This paper concentrates on the research into the applications of solar collectors, although the use of other energy conservation measures will be briefly mentioned in order that the solar collector work may be seen in perspective.

The B.R.E. research programme on solar collector applications began in 1974, as a result of the conclusions of the B.R.E. Working Party on energy conservation in buildings, which were published in 1975 (B.R.E. 1975). This report concluded that simple solar hot water systems installed in single family dwellings had an ultimate potential saving of about 2% of the national primary energy consumption. The total annual cost of energy for the U.K. is £16000 M, and thus the potential saving is about £300 M per annum.

The same report concluded, however, that use of solar energy for domestic hot water purposes was not cost-effective. B.R.E. policy is to research all techniques that have a significant potential saving, first to ensure that there is adequate technical knowledge available for their application if and when the economics change to justify their use, and secondly to evaluate any possible technical improvements which might improve their technical performance and/or cost-effectiveness. In the case of solar collector applications, a third and more urgent reason for carrying out research has emerged because of the great enthusiasm which sections of the U.K. public have shown for solar collector applications. Many exaggerated performance claims have been made, and there have already been many cases of customer dissatisfaction, both in respect of the solar collector equipment itself and resulting from the damage caused to buildings by its having been installed incorrectly.

PERFORMANCE OF SOLAR ASSISTED DOMESTIC HOT WATER SYSTEMS

A forthcoming book by Wozniak (1979) describes many systems in which solar collectors can be used to assist the heating of domestic hot water. This latter term is used throughout the present paper to describe water used for ablutory purposes in houses and in other buildings. Two basic systems are shown in figures 1 and 2 and will not be further described here as they are dealt with in detail by Wozniak (1979), who discusses the design and installation aspects of these basic systems and derivatives of them.

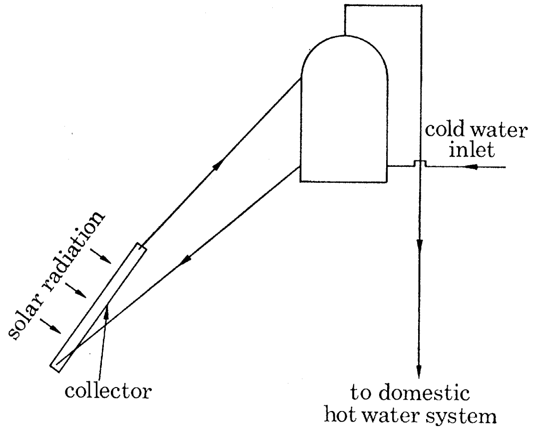

FIGURE 1. Simple solar collection system.

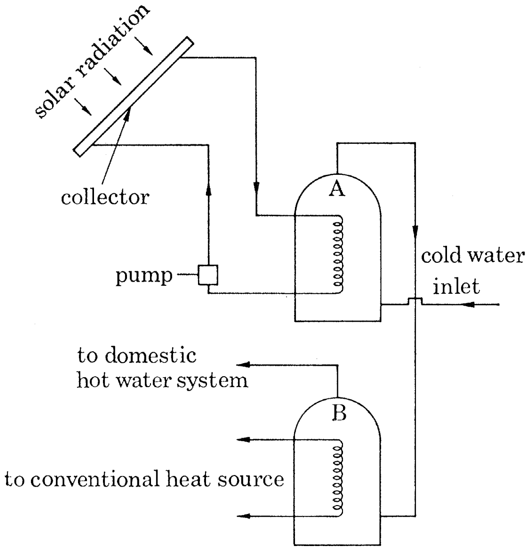

FIGURE 2. Improved solar collection system with vent pipes omitted.

This section of the paper will be devoted to a description of a completed field study which was undertaken at Tunbridge Wells High School for Girls, and also to a description of two field trials now beginning that involve (*a*) measurements of the performance of solar systems duplicated in 80 existing houses and (*b*) similar studies in 12 new houses.

Solar water heating for a school cloakroom

An experiment was carried out for the Department of Education and Science with the cooperation of Kent County Council. The building used for the experiment comprised sixth form tutorial and common rooms and was served by a single cloakroom on the ground floor. Other demands on the domestic hot water were taps in the common room and in the staff lavatory. It was known that the hot water usage in the building was low and that the original system was probably over-sized. It was none the less decided to install a solar system in accordance with design procedures based upon standard demand patterns. However, provision was made for a solenoid valve to draw off preheated water to waste in case, as expected, the usage was found to be below that for which the solar system had been designed.

The solar system comprised four collector panels having a total net area of 6.4 m^2 connected to a primary coil in a 320 l storage cylinder; this provided preheated water to the original 350 l hot water storage cylinder which was heated by off-peak electricity. The system incorporated a sealed pressurized primary circuit having a diaphragm vessel to accommodate expansion of the working fluid.

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The principal problem encountered in fixing the solar panels shown in figure 3 to the building was that the roof was insufficiently strong to support them directly, or to carry the considerable wind load that could be generated. The solution adopted was the only tenable one in the circumstances, and serves to illustrate the difficulties that may be encountered in adequately fixing collectors to some types of existing buildings. Two horizontal rolled steel joists were laid parallel to the roof and supported on uprights secured to the main steel framework of the building. Instrumentation was provided with the intention of monitoring the performance of the solar system so that the extent to which it contributed the total energy required for hot water could be determined.

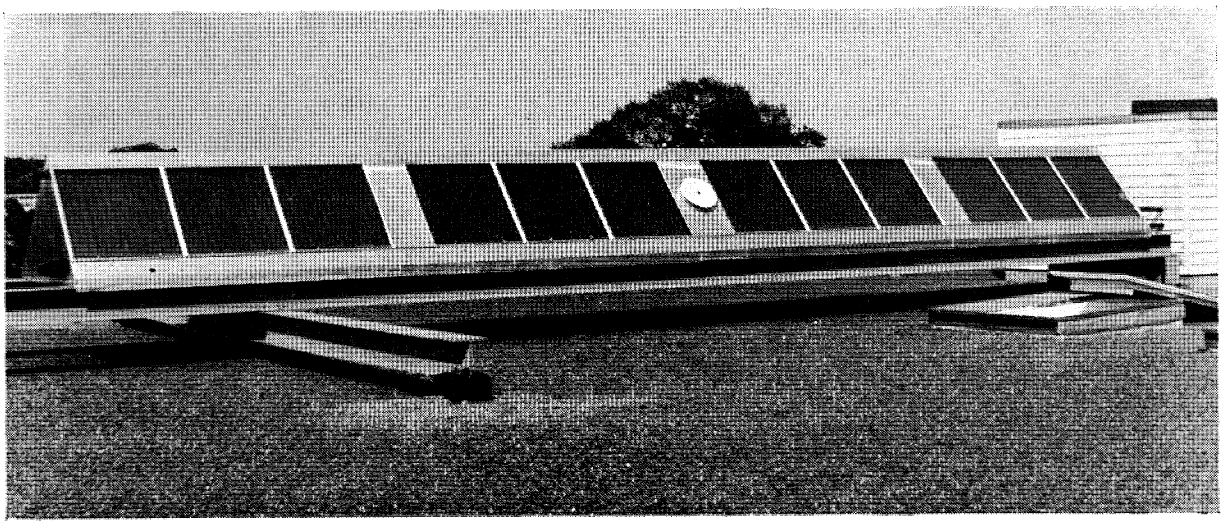

Figure 3. Solar collectors installed on school roof.

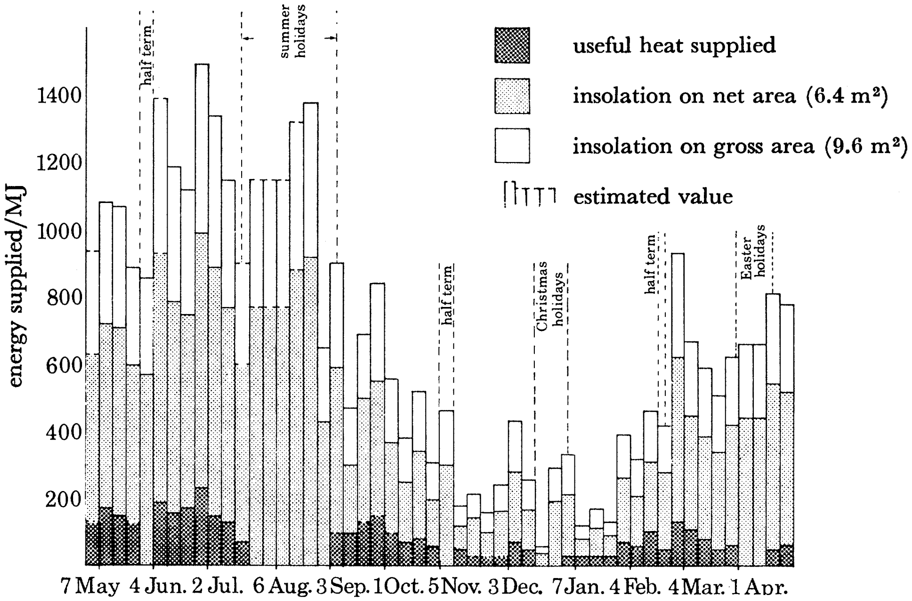

Figure 4. Histogram showing the useful energy supplied on a weekly basis; insolation onto the net and gross panel areas is also shown.

The preliminary results from the experiment are shown in figure 4 for the year May 1976–April 1977. The histogram shows on a weekly basis the total solar radiation intercepted by the collector assembly and the useful heat supplied by the system. The overall annual efficiency based on the net panel area was just in excess of 15% and the average weekly saving amounted to 20p. It should be emphasized that the efficiency figures assume that the water drained to waste by the solenoid valve was in fact usefully employed.

The radiation data were summed over seven days per week, but water draw-off only occurred during the five school days. This can help to account for the rather low efficiency values when compared with 30 or 40% that may be achieved by similar systems used in houses. It should be further noted that systems used in schools are only used for about 180 days of the year and not at all during the six weeks summer holiday, which, in the U.K. is a period of significant solar radiation.

The cost of installing this particular system was about £2000, and even if it is accepted that this is a high cost since the installation difficulties on the particular design of flat roof were great, the application is obviously far from cost-effective. This will be discussed further later; the experiment has been described in detail by Wozniak (1978).

Field trials in houses

Two major field trials of the performance of solar collectors in occupied houses have been initiated by B.R.E. The first involves 12 new houses at Basildon which are now being built. The second involves 80 existing houses. The second study is being carried out under contract to B.R.E. by the Building Services Research and Information Association and as well as forming part of the B.R.E. programme it is also part of the Department of Energy's programme on solar energy utilization.

A computer study of solar water heating by Courtney (1977) was used to investigate the effect of changes in design parameters on the performance of simple domestic solar assisted hot water system of the type shown in figure 2. The theoretical calculations showed that the annual heat output was highly dependent on the total collector area but that other changes, for example in collector slope, orientation, storage tank volume, etc, had a relatively small effect over the ranges that might reasonably be considered. However, the daily pattern of demand for water and the quantity used were shown to influence the performance significantly. It is well known (Webster 1972) that there is great variability of demand for hot water in houses. This can readily be imagined when extreme conditions of occupancy and use are envisaged: a single design of house may be occupied by a family with small children where the house is occupied all day and much use of hot water is made for washing or, alternatively, it may be occupied by a single person who is at work all day; the house therefore may only be used extensively at weekends. In order to consider a national policy for the application of solar collectors it is necessary to know what happens to the performance of solar collector systems under a range of conditions of use, so that both extreme conditions can be assessed and also the total potential saving from widespread application can be deduced more accurately than at present. Within each of the two field trials the main variable that will be explored is the influence of the occupants on the actual performance of the solar collector systems. Work on these field studies has been in hand for about a year and it is hoped to obtain firm conclusions by 1982.

Solar collector systems testing

The development of testing methods of solar collectors and solar water heating systems is being undertaken with a view to helping to establish standard test methods for use both in the U.K. and for Europe. There is close cooperation with the British Standards Institution and in particular with Professor Brinkworth, who is chairing the British Standards Committee; B.R.E. is represented both on this main committee and also on the three technical sub-committees.

The difference in the requirements for collector and system testing has led to the development of two distinct test facilities at B.R.E. and these will be described below.

In testing solar collectors, whether by transient or steady state methods (such as those drafted by N.B.S. (1976)) it is recognized that there is a need for accuracy and reproducibility in measurement in order that consistent results can be obtained: this is important in view of the fact that collectors will undoubtedly be tested by many contract laboratories and the characteristics of many solar collectors of 'standard' design may be very similar.

There are essentially two sets of problems that must be solved if reliable test methods suitable for use in the U.K. are to be developed. The instrumentation to measure such parameters as flow rate, temperature difference and irradiance must be accurate, preferably to within 1 or 2 %, and it may ultimately be necessary to have instruments certified by accredited instrument testing laboratories. B.R.E. work in selecting and proving instrumentation for solar collector testing was published almost two years ago (Wozniak 1977).

The second problem is one common to most outdoor testing and concerns the irreproducibility of any given set of weather conditions. In testing solar collectors the most difficult problem will probably be obtaining periods of time in which the radiation climate, both short and long wave, is within defined limits. No universal agreement has yet been reached either on the methods for measuring the radiation climate or on the importance that such effects may have on outdoor solar collector tests, and research is continuing. One of the problems here is that until instrumentation is standardized and accurate, the prospects for being able to measure meaningfully the effects of 'secondary' parameters such as long wave radiation and wind speed do not appear to be good.

Development of testing methods for solar water heating systems for preheating domestic hot water is an area that has been in the forefront of the B.R.E. effort. The essential problem here is, as has already been mentioned, that there are very many parameters that can effect the year-round performance of solar water heating systems, and further factors are the ratio of solar collector area to volume of preheat storage, the quality of cylinder insulation, the slope and azimuth of the solar collector panels, the quality of the collector panels, the type of control system and many more. Optimization of system design, having due regard for the costs of improving each part of the system, might eventually be possible but the present work is aimed at determining experimentally which parameters have a significant effect on system performance averaged over the year. The results from experimental test rigs will be compared to the predictions of a computer model whose preliminary output has already been published (Courtney 1977).

Depending on the experimental results the model will be modified as necessary and once it is validated against a good range of experimental data system optimization may be attempted.

Solar space heating

A house that uses solar energy for domestic hot water and for supplementary space heating was built at Milton Keynes in 1974. Monitoring of its performance by the Polytechnic of Central London supported by the Housing Development Directorate of D.o.E. has shown (Hodges & Horton 1978) that the useful heat output from the solar panels over the year 1976–7 was 2330 kW h or about 58 kW h/m²; these rather low results have been attributed partly to the frugality of the tenants but it is anticipated that changes to the energy handling system may lead to a significant improvement in the future.

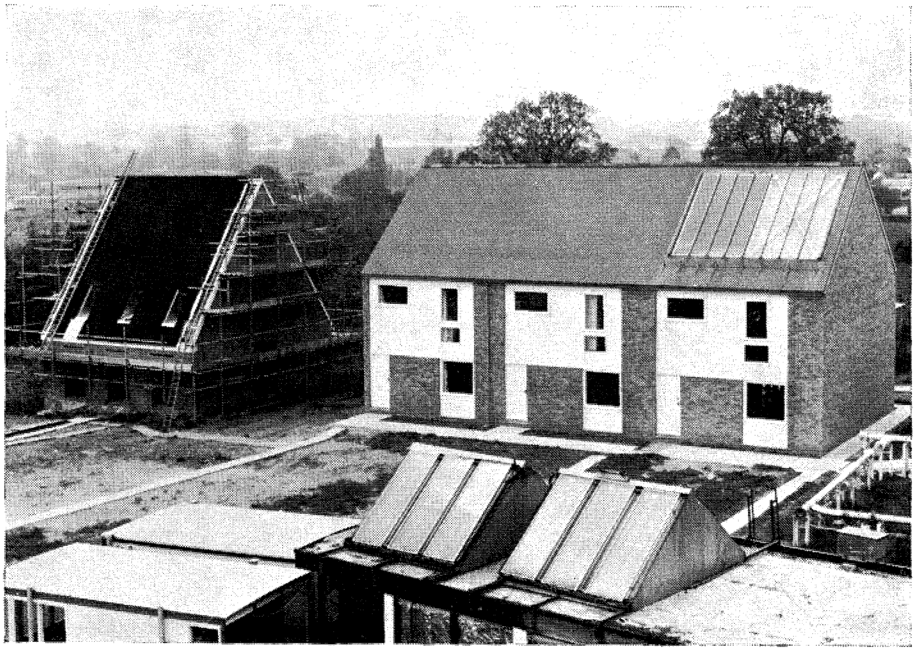

Figure 5. Four experimental low energy house laboratories at the Building Research Establishment.

Four experimental low energy house laboratories are being constructed at B.R.E. (Proc. C.I.C.C. 1977; Leach 1977) and are shown in figure 5. These involve two different construction methods – brick and blockwork with a wide cavity incorporating expanded polystyrene insulation and also timber-frame incorporating as much glass fibre insulation as can be put into the space between the outer plywood skin and the internal plasterboard. Both these construction methods have a *U*-value for the opaque part of the structure of about 0.35 W/(m² °C). This may be compared to the current Building Regulation requirement of 1.0. The unusual feature of these houses is that they incorporate in them many of the possible ways that changes could be made to building services so as to reduce energy consumption. Two of the houses incorporate solar collectors: one is an air collector and the other is a conventional flat plate collector. The air solar collector is incorporated in the house by using air source heat pumps as shown in figure 6; the services systems are shown in figure 7.

The south-facing roof slope of this house is pitched at $54\frac{1}{2}°$ and covered with matt-black painted corrugated aluminium sheet: this is in turn spaced 10 mm above a foil-covered layer (100 mm) of fibreglass which forms the main roof insulation. Air can enter the gap at the ends of the upstanding corrugations at eaves level, and is drawn up the roof to a collector plenum at the ridge. When there is significant solar radiation, this air will be warmed in its passage up the roof. In winter, about 20% of it is used as the input fresh air to the mechanical ventilation system of the house, and the remainder is ducted to the evaporator coils of the space and water heating heat pumps. These uses make the best of what will, for most of the time, be quite low temperature energy. During summer, when heating of the ventilation air is not desired, an

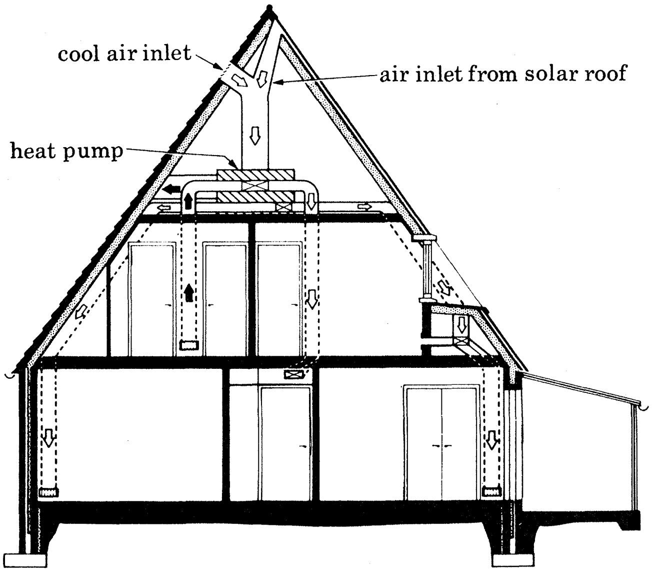

Figure 6. The experimental heat pump house.

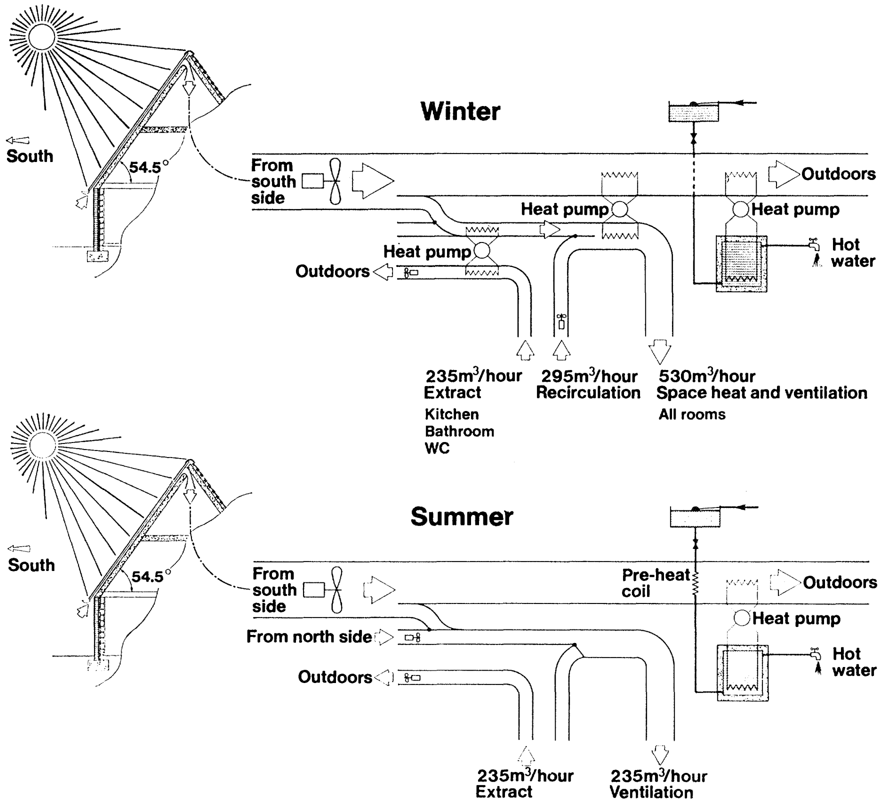

Figure 7. Heat pump house.

alternative air inlet on the north side of the house is brought into use. The whole of the air from the south-facing slope is then used for water heating, with a cold-feed preheat coil as well as the heat pump evaporator in the airstream.

On the 'solar' house, energy is collected by 20 m² of all-copper tube and fin collectors (figure 8). These have a copper oxide selective coating, and are mounted under (single) patent glazing at a slope of 42°. The primary fluid circuit is sealed, and will contain a water/antifreeze mixture. All the solar energy collected is transferred to a thermal store, consisting of 40 m³ of water in a well-insulated tank. When the collector output temperature is 1 °C or more above that of the store, energy is transferred directly by using a heat-exchanger in the base of the tank.

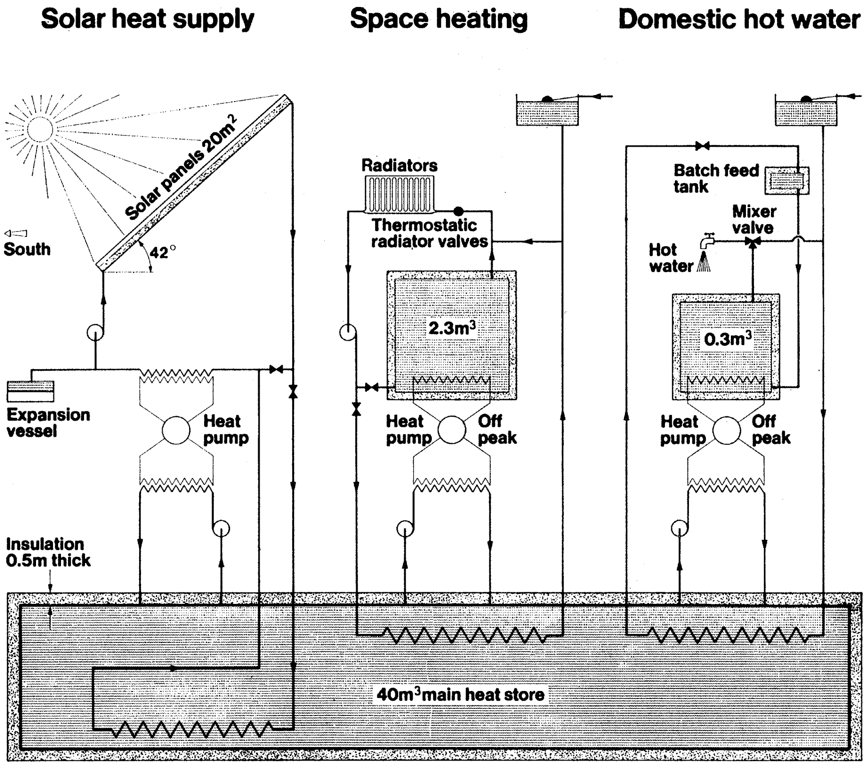

FIGURE 8. Solar house.

When the temperature difference is less (or negative) a 1 kW electrically powered heat pump can be used to transfer energy from the solar circuit, but this option will not be used throughout the year. This heat pump can also be regarded as providing an opportunity to depress the collector inlet temperature, thereby improving the collection efficiency, particularly in cold weather and under low irradiance.

The store is intended to provide (allowing for standing losses, which are considerable) the major proportion of the energy requirement for space and water heating. Energy is supplied from it to the house via two diurnal storage tanks. One of these is for space heating, feeding into extended-surface radiators sized to be adequate at flow temperatures down to 40 °C, and the other supplies the domestic hot water.

When the main store is hot enough, heat can be fed directly to the radiators, and domestic water heating may be accomplished by the preheat system. When the store is less hot, two heat pumps powered by off-peak electricity upgrade the energy into the diurnal stores, overnight. By these means it is hoped to make use of the storage capacity of the main tank between the limits of 10 and 60 °C (the probable maximum achievable temperature); without heat pump assistance the minimum usable storage temperature for space heating would be about 40 °C.

TABLE 1. CALCULATED ANNUAL PRIMARY ENERGY CONSUMPTIONS FOR THE EXPERIMENTAL LOW ENERGY HOUSE LABORATORIES

laboratory	energy consumption/GJ
'solar' house	88
heat pump house	97
house of same design but insulated only to current building regulations minimum	
all-electric	245
gas	134
house of same design but insulated to the experimental level. Conventional gas heating	122

The predicted energy savings are shown in table 1 in comparison with gas and electrically heated houses built to the current requirements of Building Regulations. During these studies, attempts will be made to assess the costs of the various elements required for widespread application of the systems. However, it was quite clear before the studies began that the expense involved in interseasonal storage of solar energy was so great that the system may never be cost effective in relation to some of the alternative methods of achieving the same ends.

COST-EFFECTIVENESS

Future B.R.E. papers concerning the appraisal of energy conservation measures in buildings will incorporate an evaluation of the internal rate of return derived from the capital costs of the conservation measure and the energy saving resulting from its use. The internal rate of return is a useful indicator: it represents the highest interest rate at which the net present value of the measure is not negative, i.e. this requires that the savings discounted back to the present at this rate just equal the present value of the cost. It avoids the use of a test discount rate and enables a comparison to be made between possible alternatives. Normal investment decisions suggest that the investment which produces the highest internal rate of return should be the one selected first. During 1979 a B.R.E. paper will be published which analyses on a common basis the cost-effectiveness of many alternative energy conservation measures that could be applied in buildings (B.R.E. 1979); among these will be included solar collector applications. It is not possible to reproduce here the conclusions of this study definitely since the work is not yet completed. However, it will be seen that the internal rate of return for solar collectors is negative and that there are many measures which give considerably higher returns and which should therefore be considered for application in the U.K. first.

I should like to thank Mr K. Seymour-Walker, Dr P. Freund and particularly Dr S. J. Wozniak, who helped in the preparation of this paper. The work described has been carried out as part of the research programme of the Building Research Establishment of the Department of the Environment and this paper is published by permission of the Director.

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Discussion

D. L. TURNER (*Department of Engineering, University of Warwick, U.K.*). Dr Leach told us that the correct time to start building and using a solar system is when the total costs of the new system are equal to or less than those of the conventional system being superseded. This is no doubt the correct choice for the individual economic man, but if society is to evolve smoothly it will be helpful to add some 'phase advance' into the control. How can this be done? All governments need income, which they raise by taxation. In a few cases taxes are designed to serve socially useful purposes: one reason why alcohol and tobacco taxes are high is because society considers that excessive consumption should be curbed. Value added tax is socially neutral – to discourage an increase in the value of goods may even be socially negative. Let us phase out v.a.t. and replace it by e.a.t., the energy added tax that has been proposed by Professor Fells, among others.

S. J. LEACH. The main purpose in evaluating returns on a wide range of investment possibilities for energy conservation is first of all to draw attention to those that show a useful return without introducing a tax on energy or other disincentives for energy use. The measures with good returns are the ones that should be acted on today, leaving the less attractive ones until later when more will be known about them. Capital is inevitably limited and choosing investments giving a good return now helps to provide further capital later when, maybe, more solar energy applications are cost-effective than is the case today. To save 10% of the Nation's primary energy consumption through investment in conservation measures giving a genuine 5% return would require an investment greater than one year's whole Gross Domestic Product for the U.K., i.e. it would require the equivalent of every single worker doing nothing else for a year or more but manufacture and install conservation measures. With investment needed on this scale there is no logic in inducing by taxation any action on measures thought not to cover their investment cost over their lifetime, such as solar domestic hot water, while there are many other measures giving excellent returns eventually generating capital.

However, I believe that the proper method for evaluating energy conservation on measures is to not use current prices but Long Run Marginal Costs for fuels which take account, for example, of the eventual need to make gas from coal again. This is more favourable to energy conservation than many assessments currently in use and will be employed in the forthcoming B.R.E. paper (B.R.E. 1979). This will improve the economic case for solar energy applications but will not bring them high up in a ranked list and hence high in priority for investment.

F. A. Holland (*Department of Chemical Engineering, University of Salford, Salford M5 4WT, U.K.*). The interest rate of return referred to by Dr Leach is the widely used discounted cash flow rate of return (d.c.f.r.r.). It is helpful to know that, in many cases, the fractional value of d.c.f.r.r. is approximately equal to the inverse of the pay back period (p.b.p.). Thus if the p.b.p. is four years, then d.c.f.r.r. = 0.25, or 25 %. The relation is strictly true if the capital investment is made as a single lump sum and the subsequent net annual cash flows based on their purchasing power in the base year are equal and extend into the future for an indefinite period. This is largely the case with energy conservation investments. A negative value of d.c.f.r.r. implies that the capital sum is never recovered, in which case a pay back period does not exist.

S. J. Leach. This is a useful simplification in certain circumstances, but breaks down when irregular maintenance, repair or replacement costs arise on the conservation measure. This is frequently the case with changes made to building services to reduce energy consumption.

J. W. Jeffery. I should like to raise some wider aspects of the replacement of fossil fuels by renewable energy sources. Fossil fuels originated hundreds of millions of years ago in a once-for-all operation before oxygen accumulated in the atmosphere. The Sun's energy, incorporated in fossil plants which have been converted into coal, oil and natural gas over countless millenia, is the Earth's energy capital. It belongs to all future generations as well as to us. Yet we treat it as though it were energy income, and even condemn true energy income – renewable solar sources – as 'uneconomical', because more labour is required to harness them than is needed to misappropriate energy capital.

From a general social point of view, taking reasonable account of the future, any project that produces more energy than is required for construction and maintenance should be considered for development. There are many criteria that ought to be considered in deciding the priorities for development: energy pay-back time, construction time, scarce materials required, labour intensity, etc. Most of these operate in the opposite direction to narrow 'economic' criteria, which are mainly concerned with minimizing the labour required. Even if labour were scarce, this would be only one of the criteria. In our present situation of massive unemployment and overmanning such 'economics' give crazy results, as Dr Leach's table of interest rates shows. The conversion of electric heating to gas, important though this is to conserve primary energy as long as we continue to use fossil fuels, comes at the top of the table, while the vitally important development of solar house heating not only comes at the bottom, but is presented as actually an undesirable development.

I suggest that it is time we used some common sense on the problem, and reserved such 'economics' for possibly deciding what incentives are required to get individual householders to cooperate in the long term conversion from fossil fuels to renewable energy sources.

S. J. Leach. I agree that converting electric heating to gas conserves primary energy (i.e. fossil fuels). This also does give a better economic return than investment in solar domestic hot water.

It is also true that investment used to replace electric heating will save substantially more fossil fuel than the same investment (i.e. amount of capital) spent on solar panels. It is therefore logical and sensible to invest first in efficient energy use rather than in solar domestic hot water, since both money and energy are saved and is not a crazy result contrary to common sense if energy conservation is the aim. The response to Mr Turner above on investment priority is also relevant.

The point is sometimes made that the coal and oil actually used for electricity production is no use for anything but burning in large power station boilers, and so we might just as well carry on using them in this way, even though the overall efficiency is 28%. However, this is not true. The same coal and oil can be used for chemical feed stocks or for making a substitute natural gas. In the latter case the energy overheads in refining and production are large, but not as large as in electricity generation hence fossil fuels are preserved by burning gas now rather than using fossil fuel based electricity for direct electric resistance heating.

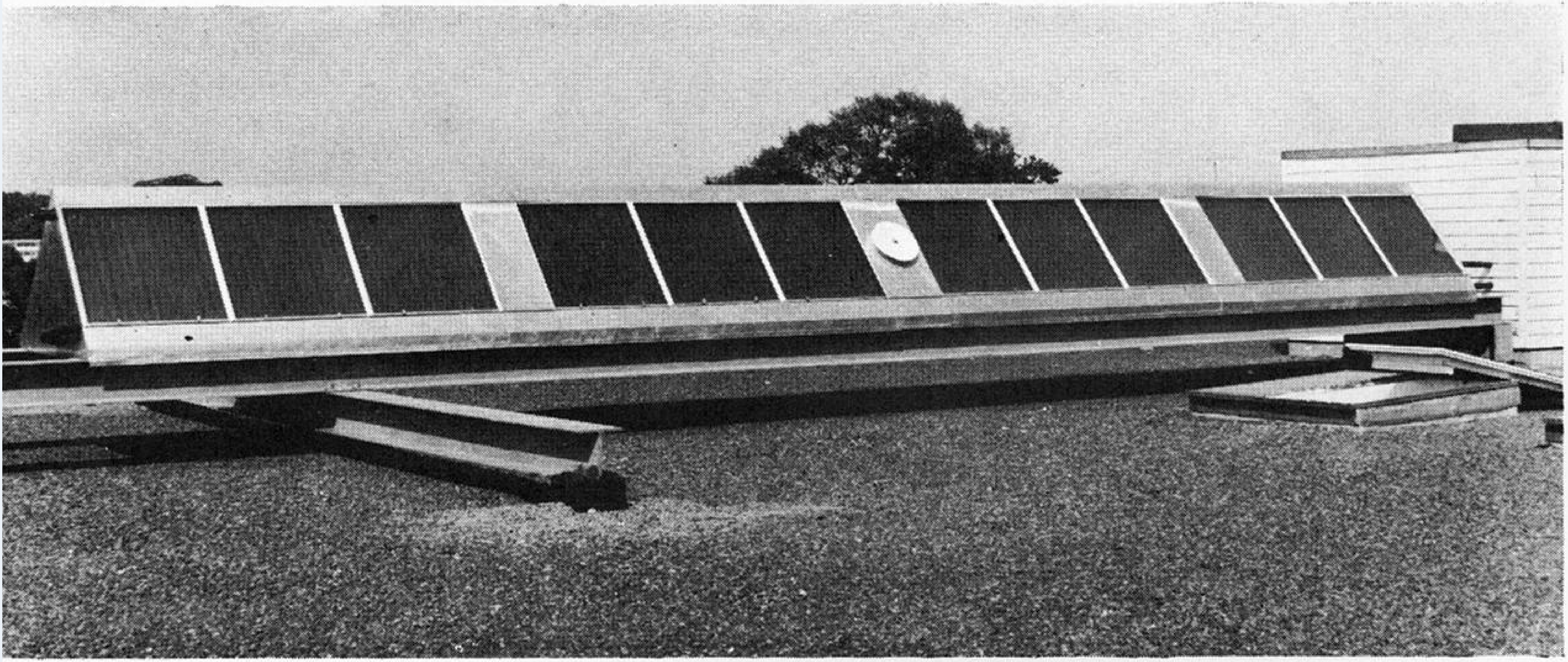

FIGURE 3. Solar collectors installed on school roof.

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