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The Energy Requirements of Buildings

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In this study a simple and accurate dynamic one-capacity model is used to investigate systematically the effect and potential of energy conservation measures on the heating requirement of buildings. The value of present and future building codes is studied under various Central European weather conditions. Three building codes are identified. For these building codes, parameter variations of the envelope, the inner part, and the operational mode of the building are performed. Three static parameters (the total heat loss coefficient, the internal capacity and the response time) and one dynamic parameter (the heating period, here defined as the number of hours with a heating requirement) turn out to be central quantities in the characterization of the thermal behaviour of a building.

INTRODUCTION

Within the Energy Systems Group at the Philips Research Laboratory in Aachen a great deal of study has been devoted to the use of alternative energy sources (*e.g.* direct and indirect use of solar energy) for heating, cooling and hot water production in buildings. Such studies have been made for both Europe [1] and various climate zones around the world [2] to determine the performance of such active systems. It was found [2] that the energy conservation measures used directly influence the performance of active systems. Moreover, for the heating and cooling of buildings, measures such as changes in the building's envelope, its control strategy and/or its associated heat storage capacity, may in general be more effective in reducing the energy demand than active measures. In short, it is already established [3, 4] that hybrid active/passive and energy conservation systems hold promise of substantially decreasing the energy demand of buildings on the one hand and, on the other hand, of substituting alternative energies for a major portion of the remaining demand. In order to assess the limitations imposed by energy conservation measures on active systems as well as to assess the potential of these measures themselves it was found necessary to look in some detail at the energy requirements of buildings.

The objective of the present study is to use a simple and accurate dynamic model [5] and systematically investigate the effect and potential of energy conservation measures. The dynamic one-capacity model used here, as well as other models, are described or referred to in [5]. This one-capacity model has been found to be accurate within a couple of percent of first principles models, which have also been verified against experiments in the Philips experimental house [6].

CALCULATIONS

Basic house types

In doing any calculations on the heating requirement of houses it is first necessary to define a set of houses which can be used as a basis. Here we restrict ourselves to single family dwellings. In particular, a building of only one shape and size is considered. This house is a two-storey structure as defined by the International Energy Agency (IEA) Task 1 [7]. Some of the relevant dimensions of this house are:

living area = 147 m^2
living volume = 314 m^3
area of building envelope = 230 m^2
(wall + roof + door + windows)

Other details are given in Table 1. Though the shape and size of this house are fixed, its basic thermal quality is determined by three

TABLE 1

Building and operation parameters for 3 basic house codes

Building parameters	Parameter values for basic house types		
	Normal house	Swedish stds. house	Experimental house
House dimensions (l/w/h)[a] [m]	12.50/5.88/4.27	as normal house	as normal house
Window areas (N/E/S/W) [m^2]	2/5/8/5		
Door area [m^2]	1.11		
Heat transf. coeff. [W/m^2 °C]:			
U-walls	1.12	0.37	0.17
U-roof	0.78	0.26	0.17
U-cellar	0.79	0.19	0.17
U-door		2.0	
U-windows (day-night)	5.8/5.8	2.24/1.5	1.9/1.2
Transmission coefficient of window panes (τ)	0.9	0.74	0.7
Absorption coeff. of walls	0	0	0
Spec. (internal) heat capacity "C_H" [kWh/°C]	40	2.4	7
Effective air exchange factor [h^{-1}]	1.58	0.87	0.3
Total heat loss coeff. [W/°C]	549.2	227.7/212.9	119.4/105.4
Response time [h]	72.8	10.7/11.4	58.6/66.4
Operations parameters	Normal house	Swedish Stds. house	Experimental house
Heating temperature (°C)	20	20	20
Effective hysteresis (°C)	0.5	0.5	0.5
Hysteresis used in program (°C)	0.14	0.5	0.14
Cooling temperature (°C)	26	26	26
Internal load (Wh, 0h - 24h)	646, 571, 565, 536, 538, 483, 749, 1566, 1744, 1563, 1263, 1227, 2128, 465, 465, 465		
Cellar temperature (°C, Jan. - Dec.)	12, 13, 14, 15, 16, 17, 18, 17, 16, 15, 14, 13		

[a] Excl. interstorey spacing.

building codes. The first of these is the so-called 'Normal House' which is defined according to the specifications of the German code DIN 4108* and is representative of the present houses in existence in the German Federal Republic. The second is the so-called 'Swedish Standards House' which is defined according to the new Swedish housing standards of 1977. The last house code considered is the so-called 'Experimental Standards House' which is defined according to the standards of the Philips experimental house. The detailed values of the parameters giving the thermal quality of these three building codes are given in Table 1. These codes define the basic house types. For codes with shutters, as indicated in Table 1 by a day/night variation of the heat transfer coefficient "U-windows", it is assumed that the shutters are used between sunset and sunrise.

The yearly heating requirement of the three house types is given in Fig. 1 for three years in Hamburg as well as for three locations in the German Federal Republic. It is found that the heating requirement of the Normal house exceeds the heating requirement of the Swedish Stds. house by a factor of 4, while the heating requirement of the Experimental Stds. house is between a factor of 35 and 50 less than that of the Normal house and depends greatly on location and year.

Clearly, the major reason for the differences in the thermal behaviour of the three house types is due to the different insulating standards given by the various total heat loss coefficients. The ratio of these coefficients is 5:2:1 for the Normal to Swedish to Experimental Stds. houses respectively; however, this ratio must be less pronounced than that of the heating requirements. This is so, since the ratio of the total heat loss coefficients is

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*1969 version.

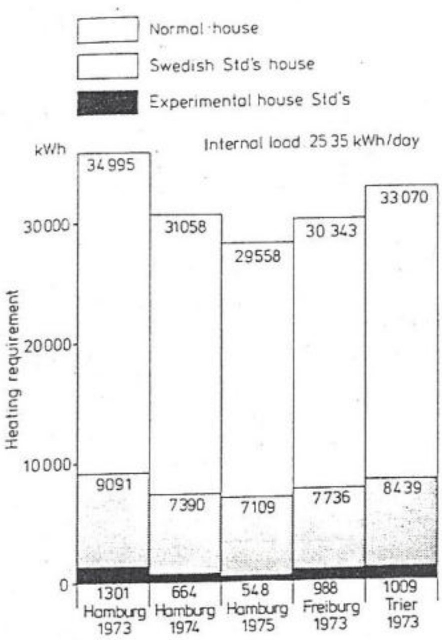

Fig. 1. Yearly heating requirements.

an exact measure only of the total energy lost per unit temperature difference to the ambient. However, the heating requirement represents a part of the total heat loss; gains such as internal loads and insolation via windows supply the remaining heat loss. Furthermore, when the heating system is off, the indoor temperature floats. Thus, dissimilar distributions of temperature differences to the ambient are found for each case. Moreover, two ambient temperatures in our model, one for the ambient air and the other for the cellar temperature, put a limit to the comparison on the basis of one heat loss coefficient per house.

The effect of changing weather conditions on the heating requirement can be estimated by comparing the yearly heating requirement for five reference years. The average yearly temperature and insolation values are given in Figs. 2 and 3 respectively. In Fig. 3 an isotropic diffuse sky was assumed. As Fig. 1 shows, the maximum variation in the yearly heating requirement is 6000 kWh for the Normal house, 1900 kWh for the Swedish Stds. house and less than 800 kWh for the Experimental Stds. house. These differences indicate a closer relation to the total heat loss coefficients than the heating requirements themselves. The reason for this is that these differences directly reflect changes in the total heat losses.

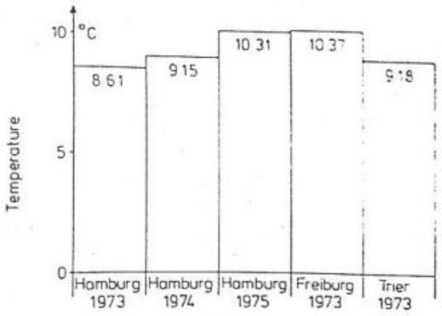

Fig. 2. Average yearly temperature.

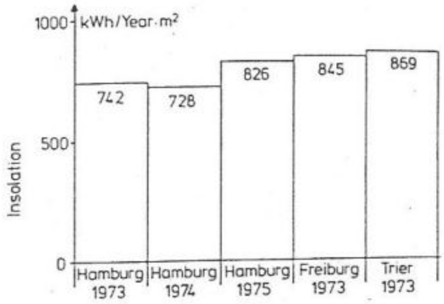

Fig. 3. Insolation on 1 m^2 area facing south.

A useful picture of the dynamics of these three house types and the net effect of the energy sources are obtained by looking at the distribution of indoor temperatures with and without a heating system. The results of such a study are shown in Figs. 4, 5 and 6 for the Normal, Swedish Stds. and Experimental Stds. house respectively. For the Swedish Stds. house a small response time* (11 h) — due to a relatively small specific heat capacity (2.4 kWh/°C) — indicates a high sensitivity to diurnal thermal variations. This may be augmented either by the ambient or the heat control system. Thus, with the heating system 'on', two strong peaks about the heating set point temperature T_h and the cooling set point temperature T_c are found. Moreover, an almost flat distribution is found with heating 'off'.

The Normal house, because of its long response time (73 h) and its bad insulation, rarely reaches temperatures near T_c. Thus, its average yearly indoor temperature is

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*Given constant ambient conditions, the response time of a house is defined as the time elapsed from the instant that all internal heat sources and solar radiation are switched (shaded) off to the instant where the difference between indoor and ambient temperature has reached 1/e of its starting value. The response time can be calculated as the quotient of the effective internal heat capacity and the total heat loss coefficient of a given house.

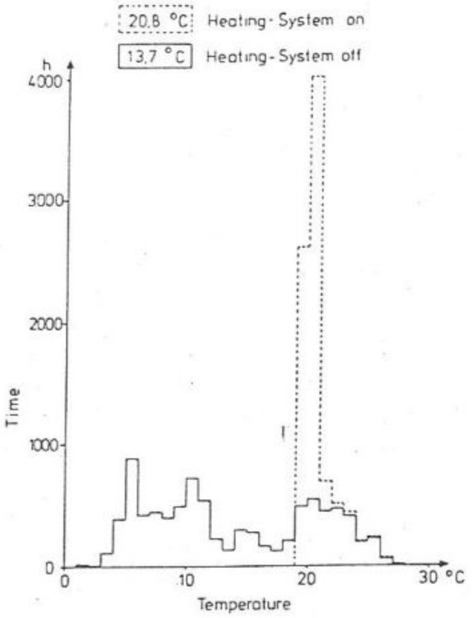

Fig. 4. Distribution of indoor temperatures for the normal house.

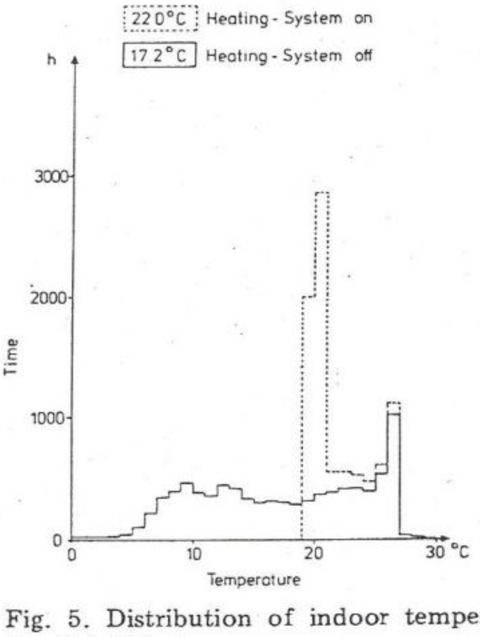

Fig. 5. Distribution of indoor temperature for the Swedish Stds. house.

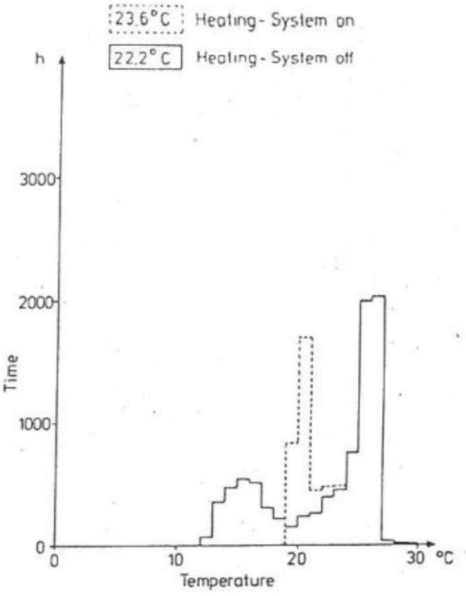

Fig. 6. Distribution of indoor temperatures for the Experimental house.

20.8 °C with the heating system turned 'on'. This is close to the heating set point. As the level of the energy sources is relatively low for this house, a low (13.7 °C) average yearly indoor temperature with the heating system "off" is found. The temperature distribution shown here almost reflects the characteristics of the ambient air temperature distribution without having the same lower limit. In both of the above-mentioned cases with the heating system 'off' the indoor house temperature often lies below any acceptable comfort range even if metabolic rates were assumed at a level of about 2 met. Looking at the results for the Experimental Stds. house (Fig. 6), it is seen that with the heating system 'off' the lowest indoor temperature reached is about 13 °C. Moreover, the yearly average temperature of 22.2 °C differs only slightly from that found (23.6 °C) with the heating system 'on'. This is a result of good insulation, a relatively large internal capacity, and energy sources which provide for the major part of the total heat losses (see Table 2).

It should be noted that in the temperature range up to 26 °C, maximum use was made of the various energy sources. In particular, no shading measures were taken nor was the number of air changes enhanced. Thus, the internal heat capacity was fully used to reduce the heating requirement. However, as shown below, a lower cooling set point (*e.g.* 24 °C) only had a minor effect on the heating requirement.

For a more detailed analysis it is necessary to consider the monthly results and to examine the gains and losses of these houses in terms of an energy balance. First of all, the effect of the energy sources, such as insolation through windows, internal loads, and contact with ambient air via window opening, is considered. The total effect of these sources on the heating requirement can be obtained by switching off all of these energy sources and comparing the results obtained with the original one. The individual contribution of any source can be estimated by computing the heating requirement with a particular source 'switched off' or 'on' when all others

TABLE 2

Yearly heating requirement and its dependence on the solar radiation through windows and internal load for the basic house types (Hamburg 1973)

	Solar radiation through windows (N:10809/S:8887/E:8407 kWh/y)	Int. load (9251 kWh/y)	Heating requirement					
			Normal (N) house		Swedish Stds. (S) house		Experimental (E) house	
			kWh/y	%	kWh/y	%	kWh/y	%
1	—[a]	—	50734	100	20374	100	10051	100
2	+[b]	—	42332	83	15232	75	5539	55
3	—	+	42375	84	12406	61	3151	31
4	+	+	34995	69	9091	45	1301	13

[a] "off"
[b] "on"

are on or off respectively. Table 2 shows the results of these calculations.

The first row of Table 2 gives the heating requirement of the three basic house types with all sources 'off' (*i.e.* the total heat loss). Comparison of row 1 in Table 2 with the original values (row 4) indicates the total effect of the additional sources, *i.e.* solar radiation through windows and energy generated by inhabitants plus appliances, and opening the windows.*

This comparison shows that the Normal house, due to its high basic needs, makes the best use of the additional energy offered. From the approximate 20,000 kWh yearly energy gains (10,800 kWh from solar radiation, 9250 kWh internal load) more than 80% are used to cut down on the energy requirements for heating. The Swedish Stds. house utilizes 63% of the 18,000 kWh available and the Experimental Stds. house uses only 55% of the available 17,500 kWh to reduce the energy requirement for heating. As rows 2 and 3 show, the internal load is used more effectively for both the Swedish and Experimental Stds. houses than the radiation through windows, whereas in the Normal house both of these sources give almost equal contributions. Given that the heating season is longer for the Normal house, this difference is due to the fact that the internal load is equally distributed over the year whereas the solar radiation is peaked towards the summer. In almost all of the cases the contribution of the ambient air, which can be made use of by opening the windows, is negligible.

The heating period is, as opposed to the total heat loss coefficient and the relaxation time, a 'dynamic' quantity reflecting not only the static thermal characteristics of a house but also the actual effect of weather conditions and the house energy system controls. In Hamburg it generally extends from September to June or a total of about 5900 h (see Fig. 4) for the Normal house, from September to May or a total of about 4800 h (see Fig. 5) for the Swedish Stds. house, and from November to March or a total of about 2500 h (see Fig. 6) for the Experimental Stds. house. These heating periods may be shortened by one month if the weather conditions are favourable as they are at locations in Southern Germany. The reason for the relatively long heating period of the Swedish Stds. house is its 11 h response time (in spite of its relatively good insulation, its specific heat capacity of 2.4 kWh/°C is too small to store enough energy to get over a cool night).

Apart from the parameters mentioned so far, two other 'dynamic' quantities are of interest for the heating system of any house. The first, the peak heating load, takes values of 16 kW for the Normal, 6 kW for the Swedish Stds. and 2 kW for the Experimental Stds. house in Hamburg. These values also reflect the values in other parts of the G.F.R. The second parameter, the average heating power demand, defines the lower limit for a

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*When the ambient air temperature is above the house temperature and the house temperature is below the cooling set point.

TABLE 3

Yearly heating requirement as a function of the internal load profile: constant hourly profiles — variation of total load

Internal load/h	Heating requirement (kWh/y)		
	Normal house	Swedish Stds. house	Experimental house
0 W (0 kWh/y)	42,332	15,232	5539
528 W (4625 kWh/y)	38,501	11,551	3067
1056 W (9251 kWh/y)	34,949	8890	1279
2112 W (18501 kWh/y)	28,390	4044	6
Basic profile (9251 kWh/y) (see Table 1)	34,995	9091	1301

TABLE 4

Yearly heating requirement as a function of the internal load profile: weekly variations

Internal load	Heating requirement (kWh/y)		
	Normal house	Swedish Stds. house	Experimental house
week: 821.3 W weekend: 1642.7 W } 9245 kWh/y	35,028	8979	1332
week: 1232.0 W weekend: 616.0 W } 9255 kWh/y	34,945	8950	1304
week: 1056.0 W weekend: 1056.0 W } 9251 kWh/y	34,949	8890	1279

heating system design. These average demands over the heating hours are 6 kW, 1.9 kW and 0.5 kW for the Normal, Swedish Stds. and Experimental Stds. houses respectively.

Variation in operating parameters

In this section, the influence of operating conditions on the heating requirement is looked at. These operating conditions are:
— internal load
— heating set point temperature
— and cooling set point temperature.
The daily sum of the internal loads is about 25 kWh/day. The basic internal load profile (Table 1) is assumed here to have the same set of hourly values for each day of the year. For this reason, three classes of variations should be studied:
— variations of the profile shape during a day
— variations of the profile shape during a week
— variations of the total internal load.

The importance of profile shape can be seen by comparing the heating requirement for a constant profile with that resulting from the original profile. As Table 3 shows, a profile distortion of this kind results in a 0.1% (46 kWh/y) change in the heating requirement of the Normal house, a 1% (101 kWh/y) change for the Swedish Stds. house and a 2% (22 kWh/y) change for the Experimental Stds. house. The absolute effect of profile changes is greatest for the Swedish Stds. house due to its low heat capacity and short relaxation time. For this type of house, more pronounced distortions of the profile shape can lead to considerably larger changes in the heating demand, especially if the hourly load exceeds the total heat storage capacity of about 14 kWh (= 2.4 kWh/°C × 6 °C). The typical variations found here due to changes of the hourly internal load profile shape with the same daily average are between 8400 kWh/y (internal load distributed during 12 hours at night) and 10,100 kWh/y (internal load distributed during 12 hours for the day) for the Swedish Stds. house. From Table 4 it can be seen that, as above, profile changes during a week (the hourly values over each day are taken to be constant) have a stronger effect on the Swedish Stds. house. However, in all cases these changes are small. The value of the total internal load is of major importance to the yearly heating requirement, as the discussion of the limiting case of zero load

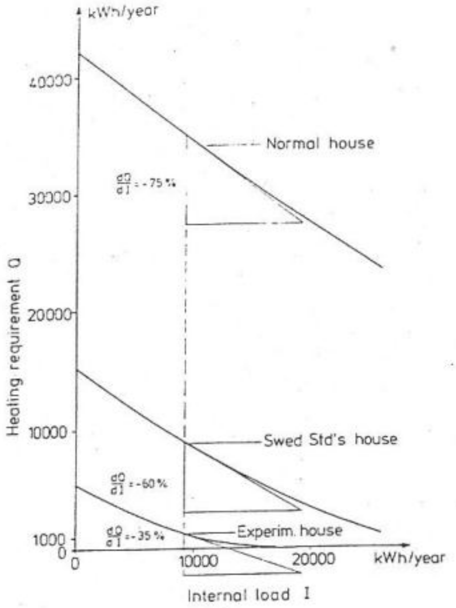

Fig. 7. Yearly heating requirements as a function of the internal load (Hamburg, 1973).

has already shown. From Fig. 7 it can be seen that for an internal load of 9250 kWh/y the change dQ in the yearly heating demand is —74% of the change dI in the yearly internal load for the Normal house, —60% for the Swedish Stds. house and —34% for the Experimental Stds. house. These percentages reflect directly the lengths of the different heating periods associated with each of these house types, relative to the maximum number of hours (8000), where heating may be necessary ($T_{\mathrm{amb}} \leqslant 19.5$ °C).

Since the thermal performance of a building is mainly determined by its conductive and ventilation losses, which are proportional to the difference between ambient air and indoor temperatures, the heating set point must have a pronounced effect on the heating requirement. It turns out (Fig. 8) that the reduction of the heating set point temperature saves, in all cases, energy without any additional investment. A change from 20 °C to 19 °C reduces the heating demand of the Normal, Swedish Stds. and Experimental Stds. house by 3700 kWh/y (11%), 1200 kWh/y (13%) and 300 kWh/y (24%) respectively. At the same time, Fig. 8 shows that a temperature increase of 1 °C for the Normal house (which is necessary to compensate for the low radiative temperature of the walls relative to the other two houses) is equivalent to an additional heating requirement of almost 4000 kWh/y.

A reduction of the heating temperature at night only has the advantage of not affecting the desired level of comfort. Doing this only has a substantial effect on thermally sensitive buildings (*i.e.* with response times $\lesssim$ 12 h). Thus, for the Swedish Stds. house a 12% reduction is obtained by having a night reduction from 20 °C to 16 °C. The reductions found for both the Normal and Experimental Stds. house are less than 2.5% of the total heating requirement. However, in practice higher reductions may be achieved, especially for the Normal house. This is mainly a result of avoiding additonal parasitic losses (*e.g.* heating losses due to uninsulated piping and radiator niches) during the night. These parasitic losses are not accounted for in this model. Another point is that the temperature of the one-capacity model used here does not exactly reflect the internal air temperature of the house during the heating-up period in the morning.

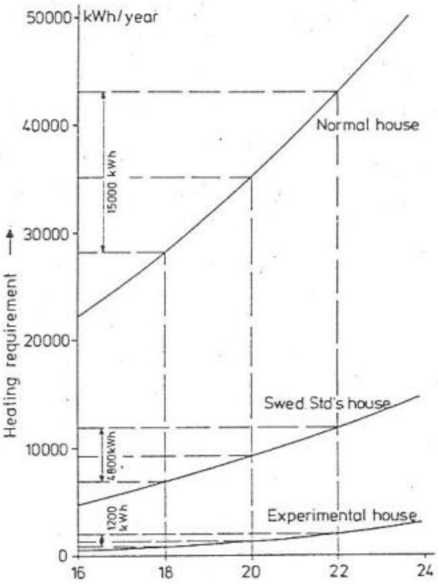

Fig. 8. Yearly heating requirements as a function of the heating temperature (Hamburg, 1973).

Thus, in practice the internal heat capacity will stay at a lower average temperature in the morning and therefore lose less energy to the ambient. However, this saving is reduced due to higher air exchange losses because in a real system the air temperature has to be raised to compensate for the lower radiative temperature of the walls in the morning. A more complete analysis of this point must therefore include these features. Such a study with a refined model is being undertaken.

The variation of the cooling set point temperature about a value of 26 °C was found to have only a small effect. Thus, it is possible to reduce the cooling temperature set point to 24 °C and so improve the comfort conditions without increasing the yearly heating requirement by more than some 340 kWh, 40 kWh and 10 kWh for the Normal, Swedish Stds. and Experimental Stds. houses respectively.

Variation of building parameters

In this section variations of the building parameters and their effect on the heating requirement are studied. The parameters considered here are:

- window type and area
- wall insulation
- air infiltration
- solar absorption coefficient of walls
- internal heat capacity.

A parameter variation which is often considered to be promising in reducing the heating requirement is that of increasing the south-facing window area. The effect of such changes has been studied for the three house codes and also for various years in Hamburg and various locations in the G.F.R. Moreover, for the Normal house a variation of window and shutter quality has also been made.

To obtain a more detailed insight into the thermal effect of other windows, it is of interest to start off with a building having no windows at all; then, one by one, windows to the north, east and west with areas of 2 m^2, 5 m^2 and 5 m^2 respectively are added. The area of the south-facing window is then increased from 0 until almost the whole south wall is covered. The results of this parameter variation can be seen in Fig. 9 for the three house codes in Hamburg 1973.

It is found that improving the thermal quality of windows has a sizable effect for the Normal house. For the normal window dimensions as given in Table 1 the introduction of shutters (U-shutter = 4.0 W/m^2 °C) to the Normal house leads to a 4000 kWh/y (or 11.5%) decrease in the heating requirement. When equipping windows with special insulating shutters (this is a tight shutter with an IR-reflective coating on the inside: U-shutter = 0.9 W/m^2 °C), a 5800 kWh/y (or 16.5%) saving can be achieved. The improvement of single pane windows to double or triple pane windows in the Normal house combined with shutters (U-shutter = 4.0 W/m^2 °C) reduces the heating requirement by 5600 kWh/y (or 16%) or 6500 kWh/y (or 18.5%) respectively. Installing only a double pane window with no shutters results in a 4500 kWh/y (or 13%) reduction with respect to the single pane windows for the Normal house. These numbers indicate that double pane windows without shutters are almost thermally equivalent to single pane windows with shutters and double pane windows with shutters are equivalent to single pane windows with special shutters.

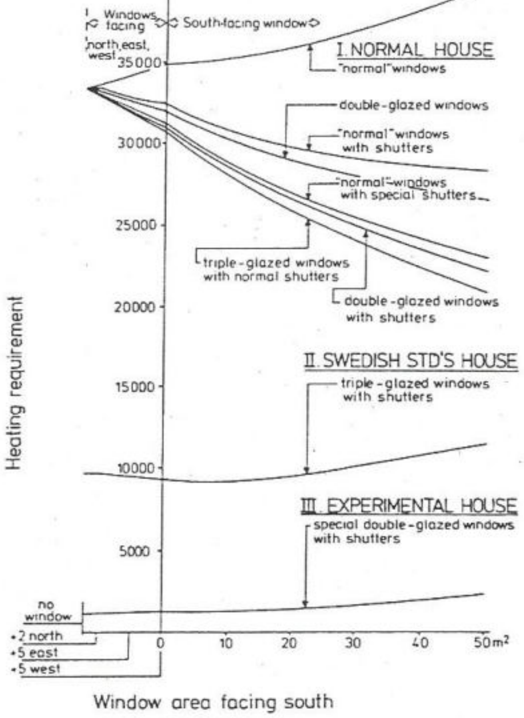

Fig. 9. Heating requirements as a function of the window area (Hamburg, 1973).

From Fig. 9 it is seen that for the Normal house with its normal windows (*i.e.* single glazing, no shutters) there is only a net loss with increasing window area. However, as soon as good shutters are introduced which decrease the night-time losses, only energy gains are obtained with increasing window area. Savings of up to 14,000 kWh/y (or 40%) would be realized if the whole south-facing wall (about 50 m^2) were fitted with triple pane windows and shutters. However, due to the increasing influence of the radiative temperature of the windows, such a measure is not a sensible one as it would drastically affect the comfort level of the occupants, implying that a variable house temperature would have to be set to compensate for varying radiative temperatures. Before any economic optimization can be carried out with respect to window area, the effect of such temperature settings needs to be investigated.

The result of an increase of the south-facing window area on the two wall insulated house types is quite different. One, the Swedish Stds. house, has a flat thermal optimum, whereas the other, the Experimental Stds. house, does not. The reason for this behaviour in the Experimental Stds. house is that the walls are so good that even the best windows (U-window (day/night) = 0.8/0.6 W/m^2 °C, $\tau = 0.6, 0.0$) can barely gain enough solar radiation during the day to substitute for the losses incurred at night relative to the wall. The Swedish Stds. house, on the other hand, does not have such a good wall insulation and moreover operates over almost double the heating season of the Experimental Stds. house. Thus, there is a set of (sunny) days where solar energy can be gained through windows over the day and transferred to compensate for losses at night. However, the house has a finite total heat storage capacity of only 14.4 kWh so that beyond a certain south-facing window area, each additional m^2 just adds to the nighttime losses without transferring any net gain. For the other set of days (cloudy) hardly any gain is made over the day. Thus, increasing the window area further only leads to additional losses. In this way a flat thermal minimum for the Swedish Stds. house is obtained. This optimum varies between 8 and 12 m^2 depending on location and year in the G.F.R. This window area is in fact very close to the DIN regulations for a house of this size.

As far as improvements in the thermal quality of windows for the heating requirement of a house are concerned, it should be noted that an improvement in the heat loss coefficient is usually accompanied by a decrease in the transmission coefficient. To assess this, a sensitivity study with respect to these coefficients was done for the three house types given in Table 1. The results indicate that a decrease in the transmission coefficient of 0.1 can only be compensated by decreasing the heat loss coefficients by 0.36, 0.26 and 0.22 W/m^2 °C for the windows of the Normal, Swedish Stds. and Experimental Stds. houses respectively.

Besides the windows, the walls are a weak point of the Normal house. A comparison between the Normal, Swedish Stds. and Experimental Stds. houses has already shown the considerable effect that good insulation can have on the heating requirement. In order to get a more precise picture, calculations were made for the heating requirement of these house types as a function of additional insulation. Figure 10 shows that only small savings can be realized by further increasing the insulation thickness of the Swedish and Experimental Stds. houses. A substantial reduction, however, can be achieved for the Normal house. For example, 1 cm of additional insulation results in a 4000 kWh/y savings whereas 5 cm gives a saving of 11,000 kWh/y. It was found that the asymptote for insulation effects for the Normal house lies at about 16,000 kWh/y or a saving of about 19,000 kWh/y. This remaining large heating requirement is due to the poor windows, infiltration losses, and cellar losses.

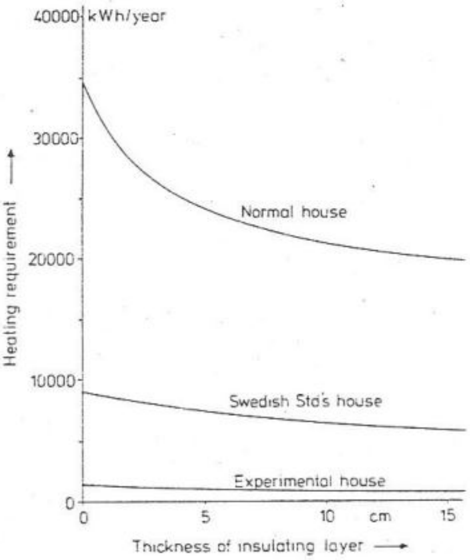

Fig. 10. Yearly heating requirement as a function of the additional wall insulation (Hamburg, 1973).

The effect of controlled and uncontrolled ventilation losses as described by the effective air changes per hour is given in Fig. 11. This has a sizable effect on the heating requirement of all three houses. As seen from Fig. 11, once a well insulated and tight house

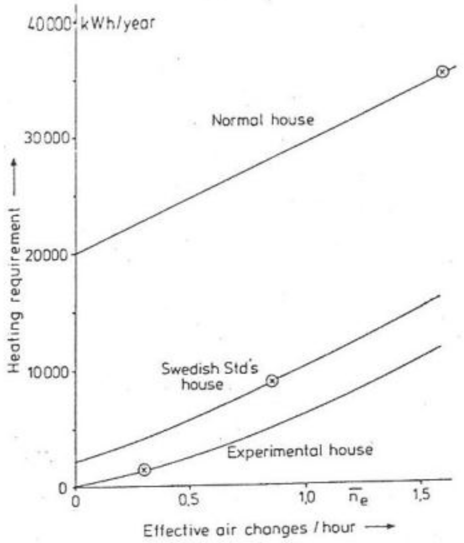

Fig. 11. Yearly heating requirement as a function of the effective air changes per hour (Hamburg, 1973).

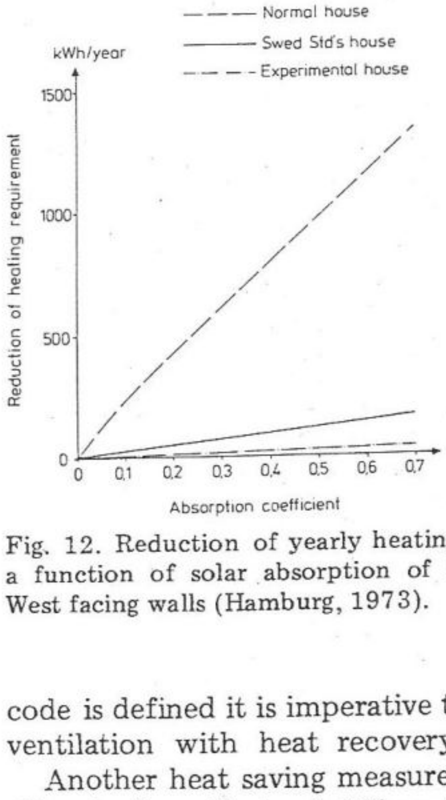

Fig. 12. Reduction of yearly heating requirement as a function of solar absorption of East, South and West facing walls (Hamburg, 1973).

code is defined it is imperative that controlled ventilation with heat recovery be installed.

Another heat saving measure one may consider is the effect of different non-selective colored paints covering the east, south, and west walls. The effect of this measure is that solar radiation is absorbed on the outside wall surface and the heat requirement is reduced due to an increased outside wall temperature. Figure 12 shows the reduction which may be achieved for a wall with an absorption coefficient between 0 and 0.7. Because of the good insulation of the Swedish and Experimental Stds. houses relative to the high (~ 24 W/m^2 °C) total ambient heat transfer coefficient* and their shorter heating seasons, only a minor effect due to absorption is observed for these codes. However, for the Normal house up to 1500 kWh/y (~ 4%) can be saved.

Due to its storage function the internal heat capacity influences the heating requirement. As already mentioned above, it is only necessary to consider the Swedish Stds. house here. Figure 13 shows that the heating demand of the Swedish Stds. house is not too strongly dependent on the effective heat capacity. A reduction of about 1000 kWh (11%) is achieved by increasing the capacity of the Swedish Stds. house from its normal value of 2.4 to 10 kWh/°C (*i.e.* from a 1/3 of a day storage capacity to a daily storage capacity). Beyond this size only a negligible change is observed until one reaches the level of a weekly storage capacity (*i.e.* about 50 kWh/°C for the Swedish house). With this capacity, one can now bridge over short bad weather periods.

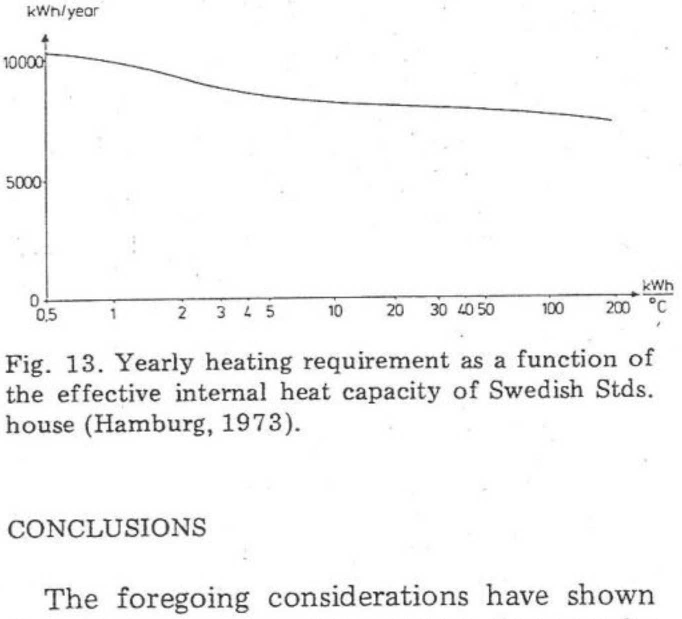

Fig. 13. Yearly heating requirement as a function of the effective internal heat capacity of Swedish Stds. house (Hamburg, 1973).

CONCLUSIONS

The foregoing considerations have shown that there are various measures that can be used for decreasing the energy requirements of houses. It was observed above that the effectiveness of a given measure strongly depends on a building's defining parameters. These parameters can be conveniently summarized by three typical constants, namely, the storage capacity, the total heat loss coefficient and the response time. Improvements in a building's envelope (*e.g.* windows, insulation, absorbing walls, tightness) mainly affect the Normal house due to its high basic total heat loss coefficient. A better effective storage capacity, however, mainly affects the

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*Convective plus radiative.

Swedish Stds. house because of its low storage capacity. The effectiveness of any time-dependent measure, such as other temperature control strategies, is strongly dependent on the sensitivity of a building (*i.e.* its response time). Accordingly, a day-night reduction mainly influences the performance of the Swedish Stds. house.

Another quantity that was introduced above was the heating period. This parameter gives the number of hours per year where an actual heating requirement existed. Only during this period can an additional measure result in any saving.

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