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Energy use during the Life Cycle of Single-Unit Dwellings: Examples

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The energy use during the life cycle of three single-unit dwellings built in Sweden in 1991 *and* 1992 *is presented. These houses were prefabricated and their frameworks are made of wood. The purpose of this study is to gain an insight into the energy use for a dwelling during its life cycle. The method used is described in the companion paper "Energy use during the life cycle of buildings: a method"* [*Building and Environment*, 1997, **32**, 317–320]. © 1997 *Elsevier Science Ltd.*

BACKGROUND

Three single-unit dwellings were studied with regard to the energy use throughout the life cycle. The dwellings were built in Sweden in 1991–1992. Figures 1–4 present the exterior and construction of the dwellings. They are ordinary single-family dwellings, prefabricated in a factory. The factory manufactures external wall and joist elements which then are transported to the building site. The facades of the houses are covered with wooden panelling, and the frames are made of wood. The insulating material in the walls and roofs consists of glass wool. The roofs are covered with concrete roofing tiles.

Table 1 presents some of the dwellings' characteristics. The airtightness varies between 2.1 and 3.8 $m^3/(m^2\,h)$ at a differential pressure of 50 Pa across the building envelope, which may be considered "normal". According to the Swedish Building Code, airtightness in dwellings must not exceed 3.0 $m^3/(m^2\,h)$. The airtightness is stated in the unit $m^3/(m^2\,h)$ when there is a differential pressure of 50 Pa between the inside and the outside. During occupancy, the differential pressure between the inside and the outside is assumed to be 2.5 Pa.

The dwellings are equipped with mechanical supply and exhaust air ventilation. The heat in the exhaust air is heat-exchanged into the supply air before the exhaust air is released into the open air outside. The efficiency of the heat exchanger is assumed to be 50%. The dwellings are heated with hot air. To safeguard maximum economy in the use of installations and components, heating systems are integrated with the ventilation of the dwellings. The supply air is heated to a maximum of 40°C (depending on the heating requirement); consequently, it conveys both air and heat at the same time.

The rate of air change in the dwellings (see Table 1) is higher than the average value for a single-unit dwelling in Sweden. That average is 0.29 $l/(s\,m^2$ usable floor area), which corresponds to roughly 0.4 air-change rate/hour [1].

External walls, floors and roofs/ceilings are well insulated, but not unusually so for Swedish conditions. Variations in the outdoor temperature and solar radiation in

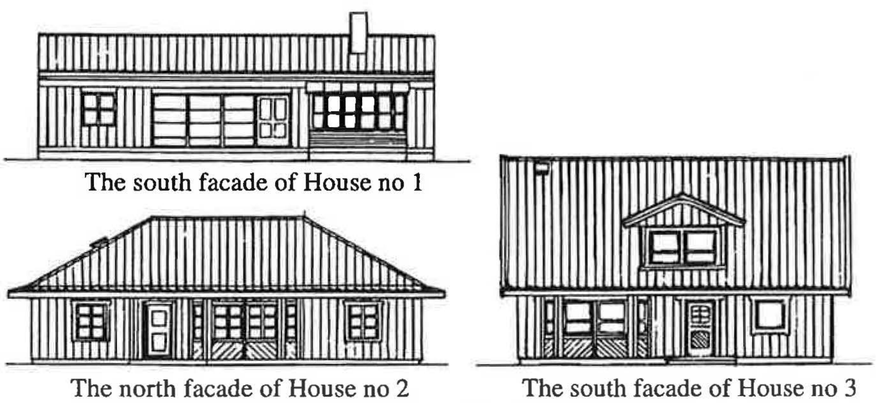

Fig. 1. The exterior of the dwellings.

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Table 1. Essential data concerning the three houses in the study

Unit	Unit	House 1	House 2	House 3
Usable floor area	m^2	130	129	138
Volume	m^3	347	310	315
Inhabitants	—	5	5	5
Number of floors	—	1	1	2
Airtightness at a differential pressure of 50 Pa	$m^3/(m^2\,h)$	3.8	2.4	2.1
Indoor temperature	°C	20	20	20
Air-change rate	h^{-1}	0.7	0.8	0.6
U values				
Roof	$W/(m^2\,K)$	0.09	0.09	0.09
External walls	$W/(m^2\,K)$	0.15	0.17	0.17
Foundation	$W/(m^2\,K)$	0.26	0.27	0.29
Door	$W/(m^2\,K)$	0.69	0.69	0.69
Windows	$W/(m^2\,K)$	1.63	1.36	1.36
Area of the windows				
North	m^2	4.6	6.8	6.0
East	m^2	3.4	—	5.5
South	m^2	15.6	8.4	10.0
West	m^2	1.1	1.4	2.8

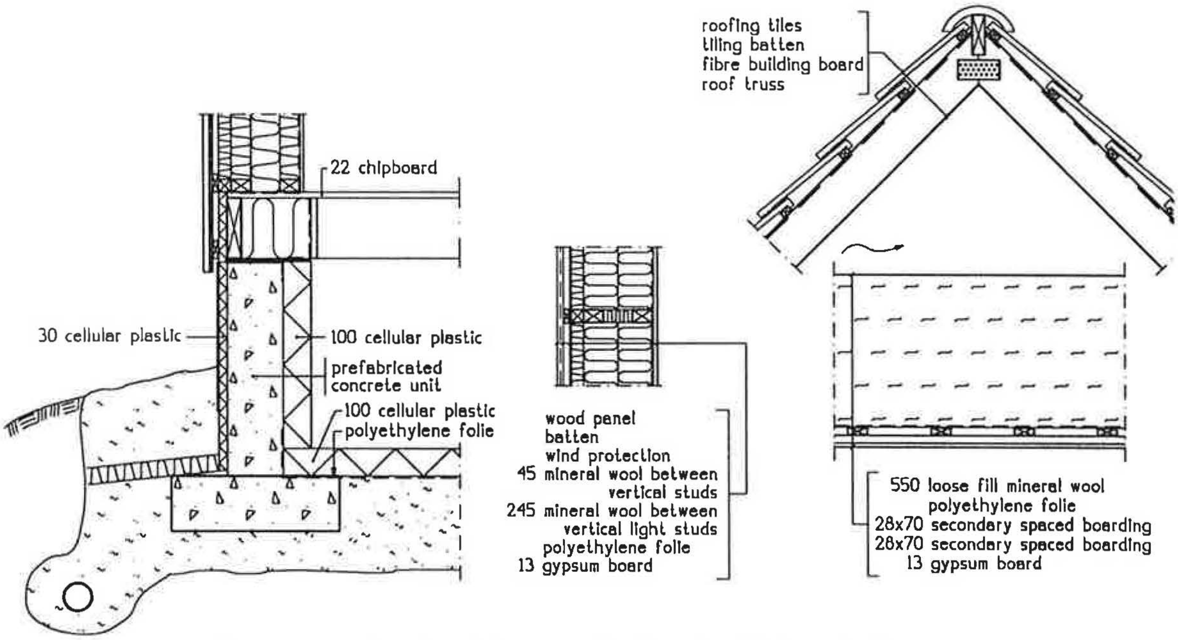

Fig. 2. Different constructions: foundation, external walls and roof in house 1. All measurements in the figure are in mm.

the area within which the dwellings have been built are shown in Fig. 5.

RESULTS

Manufacturing energy use during production and renovation

In order to estimate the energy required in manufacturing the construction materials, the quantities of building materials must be calculated. In this case, however, the amount of macadam, joint glue and putty, as well as ventilation equipment and supply and exhaust air devices, have not been included. The reason for this is that no data on the manufacturing energy pertaining to these materials and appurtenances were available.

Figures 6 and 7 present the quantities of materials in the dwellings and the energy requirements associated with manufacturing the building materials. The m^2 refers to m^2 of usable floor area (the gross floor minus the external wall area) in the dwelling concerr

Concrete comprised the major share of the struction materials used in the three single-unit dwelli Concrete accounts for 65–75% of the total weight qu tity. Next in line is wood, at 12–21% by weight, and gypsum with 6–7%. The reason for the large propor of wood is that the three dwellings have wooden panel and wooden frames.

It is interesting to observe the proportion of plas expressed as a quantity, in Fig. 6 and to relate it to manufacturing energy requirement shown in Fig. 7. weight of plastics is between 1 and 2%, whereas manufacturing energy related to plastic mate amounts to no less than 18–23% of the entire am required for the three dwellings!

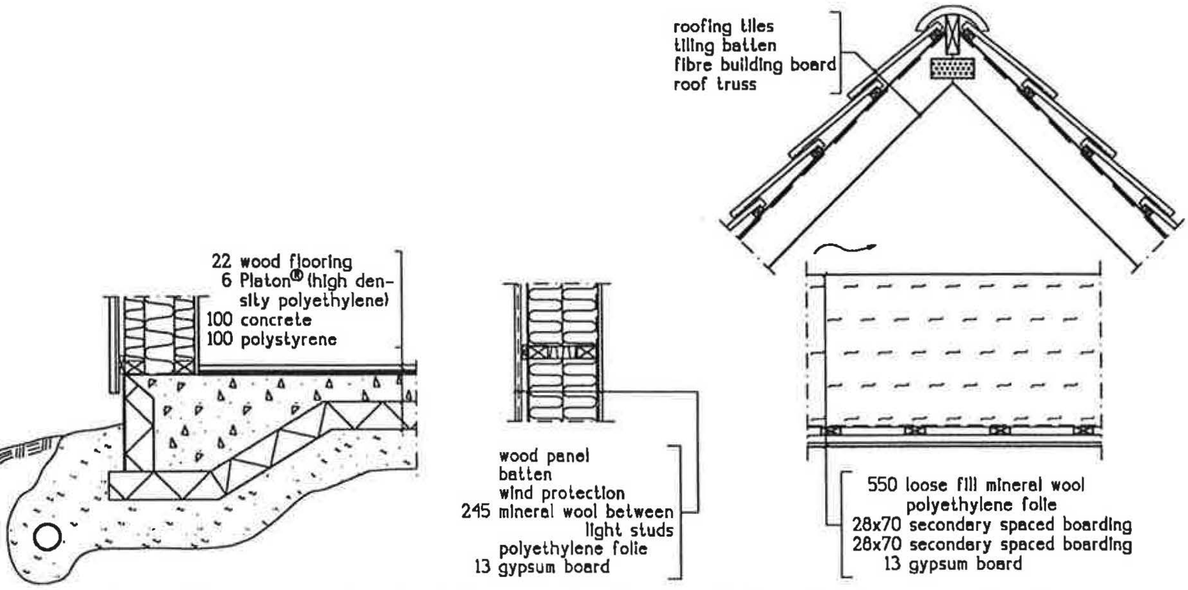

Fig. 3. Different constructions: foundation, external walls and roof in house 2. All measurements in the figure are in mm.

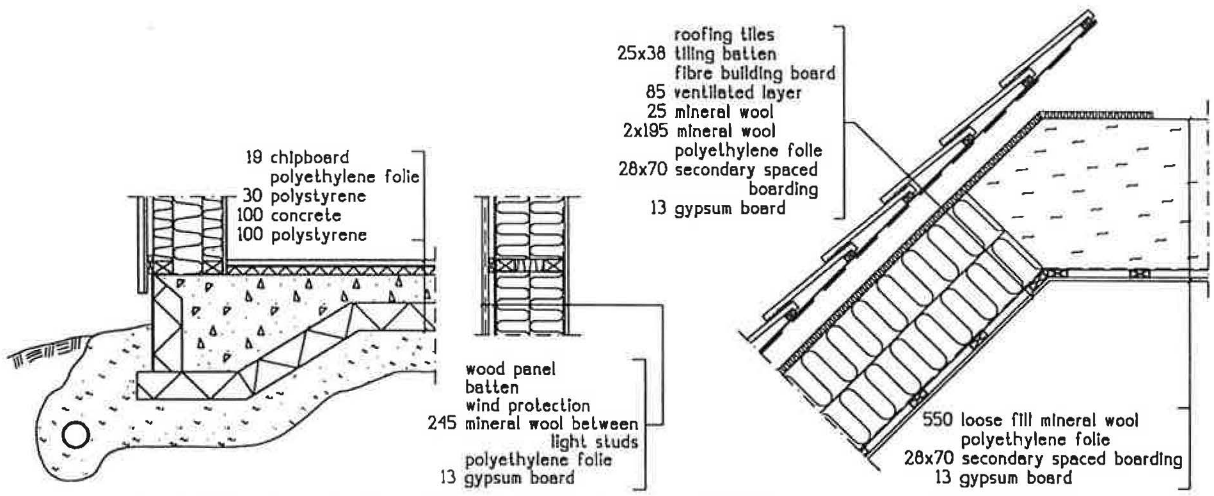

Fig. 4. Different constructions: foundation, external walls and roof in house 3. All measurements in the figure are in mm.

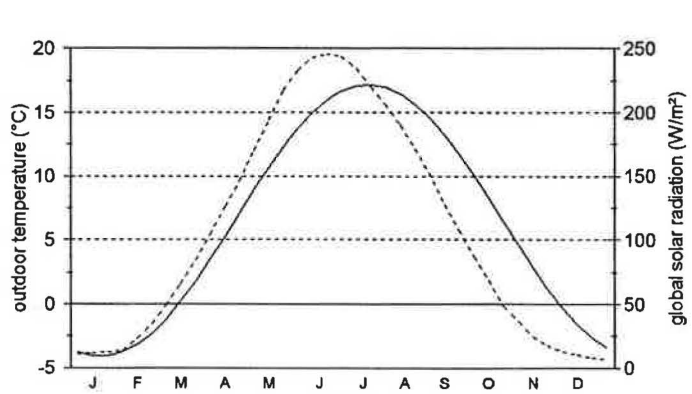

Fig. 5. Outdoor temperature (city of Västerås) and global solar radiation (suburb of Bromma near Stockholm) in relation to the horizontal surface during the year [2]. The two locations are geographically close to the three dwellings studied. The average annual temperature is 5.9°C.

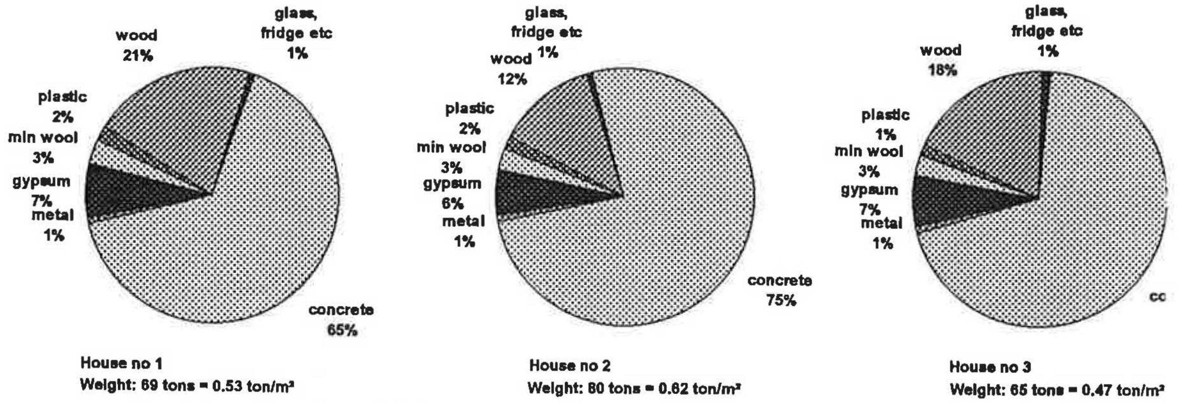

Fig. 6. Quantities of materials in the three dwellings. The dwellings weigh 65–80 tons, corresponding to 0.47–0.62 ton/m^2 usable floor area.

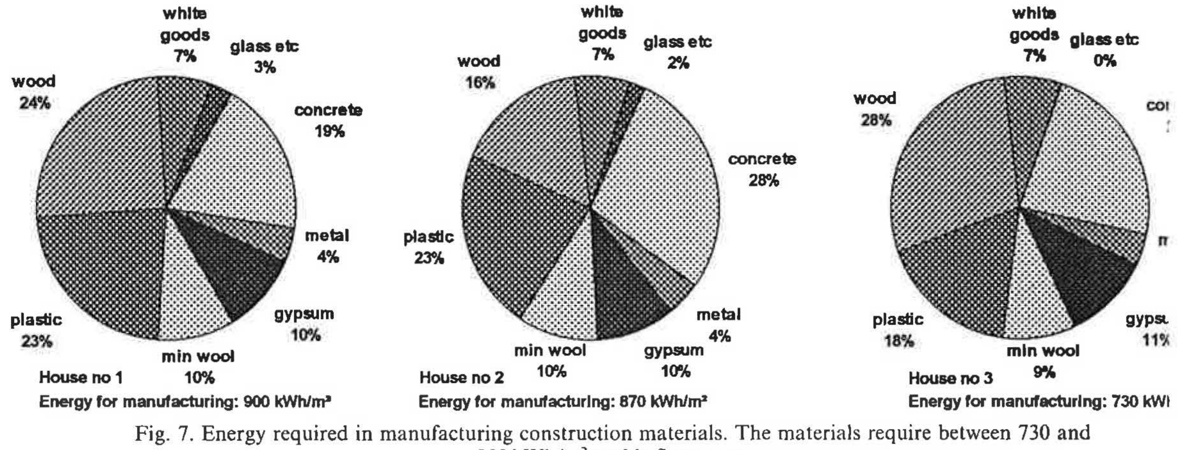

Fig. 7. Energy required in manufacturing construction materials. The materials require between 730 and 900 kWh/m^2 usable floor area.

The proportion of concrete in Fig. 6 and the relevant manufacturing energy requirement in Fig. 7 may also be compared. While the weight of the concrete used in the three dwellings amounts to 65–75% of the whole, the energy used for manufacturing concrete only accounted for 19–28% of the entire manufacturing energy requirement of the dwellings. In other words, the pattern of distribution with respect to energy requirement is very different from the percentages by weight.

The amounts of energy used in manufacturing the construction materials in houses 1, 2 and 3 are 900, 870 and 730 kWh/m^2 usable floor area, respectively. The reason for the lower energy use/m^2 usable floor area of dwelling number 3 is because it is a two-storey dwelling.

Based on assumptions regarding the life-spans of various materials (presented in Table 2 in the companion paper "Energy use during the life cycle of buildings: a method" [3]), the quantity of renovation materials may be calculated. The relevant quantities are presented in Fig. 8. Figure 9 shows the energy used when manufacturing renovation materials.

A large proportion of the renovation materials is made up of concrete (see Fig. 8). The reason for the preponderance of concrete is that the roofing tiles of the houses are made of this material. Even so, a large share of the energy required for manufacturing "renovation materials" is associated with white goods and plastic products (see Fig. 9). This is because the life-span of white goods is no more than 12 years and that of pl is only 17 years.

Energy use for transportation during the production, r vation and destruction

Materials are transported from their manufacture the building site both during the erection phase and ing renovation. In the case of renovation and demoli "worn out" materials will also be removed. Figu presents the movement of transport during the duction of the three single-unit dwellings.

When construction materials are removed, in the of renovation or demolition, the transportation r look different. This study assumes that there is a v disposal plant in the municipality where the three d ings are located. The relevant transportation distar assumed to be 20 km.

Figure 11 is a bar chart illustrating the transport er used in connection with production, renovation destruction. The discrepancies in the transport er associated with production are due to different quan of materials, as well as to the relative locations o factories where the elements are prefabricated, the m facturer of the materials and the building site. Tran energy during renovation is much the same for the dwellings. The differences in transport energy d destruction are solely due to dissimilar quantiti materials.

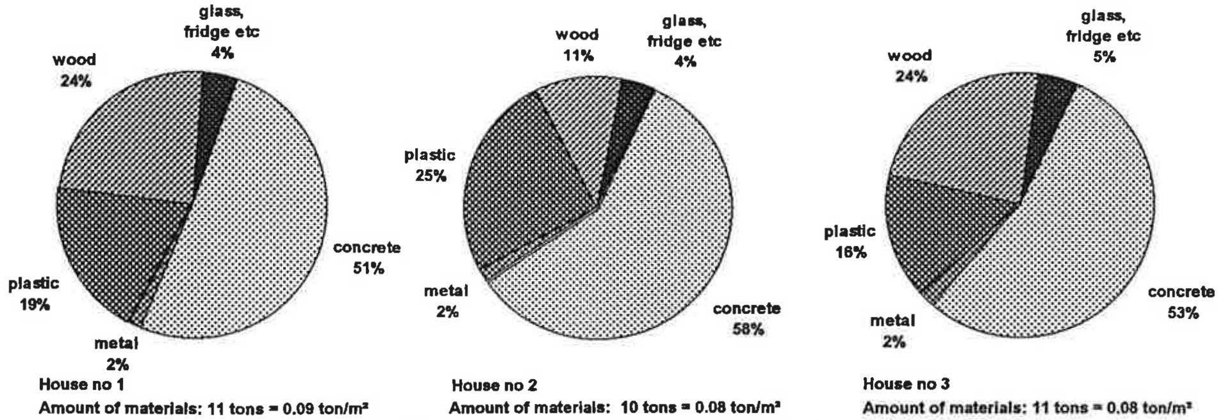

Fig. 8. The quantities of renovation materials.

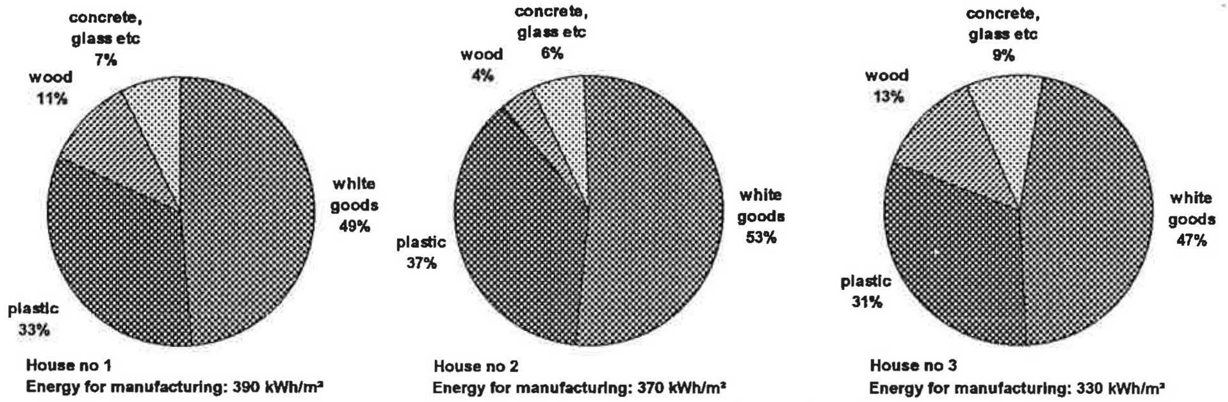

Fig. 9. Energy used when manufacturing construction materials employed in the renovation.

Energy use during the erection and demolition

During the erection and the demolition of buildings, energy is required for a variety of processes. Figure 12 shows the calculated energy use during the erection and demolition of the three dwellings.

A large share of the process energy used during the construction of the dwellings is required for space heating at the building site and for the excavation and the removal of soil.

The main reason for the difference in the process energy used during the construction of the dwellings is due to the quantity of soil that is to be excavated and removed (see Fig. 12). House 1 needs more energy for the excavation and removal of soil than the others, as it has a foundation with crawl-space, whereas the others are slab-on-ground buildings. A crawl-space fundament is placed deeper in the soil than a slab on the ground, which is why more soil had to be removed.

It can also be seen from Fig. 12 that the energy used for desiccating the frame varies. This is due to the fact that more energy is used to dry the slabs in houses 2 and 3 than is used for the crawl-space of house 1, which has a wooden floor structure.

Energy use during the occupation

During the years when the dwelling is actually inhabited, energy is required for space heating, hot water and electricity. The energy use during this period was calculated with the aid of the Swedish computer program Enorm [4] (see also the companion paper "Energy use during the life cycle of buildings: a method" [3]).

The people who live in the dwellings are able to influence the utilisation of energy, e.g. indoor temperature, hot water use and electricity. However, the indoor temperature has been assumed to be 20°C throughout. Standard values have been employed in the calculations of the energy requirements regarding hot water and domestic electricity. They were estimated according to the following procedure:

- hot water: $5 \times$ number of apartments $+ 0.05 \times$ usable floor area (kWh/24 hours);
- domestic electricity: $4.5 \times$ number of apartments $+ 0.045 \times$ usable floor area (kWh/24 hours).

The standard equations were based on an investigation of 8000 households in Stockholm in the years 1972–1984 [5].

Table 2 presents the energy used during the occupation. The various assumptions and characteristics pertaining to the dwellings studied were described above. No account is taken of any energy required for the cooling of the dwelling in the case of excessive indoor temperature. This could occur during the summer months.

The energy required for heating, domestic hot water

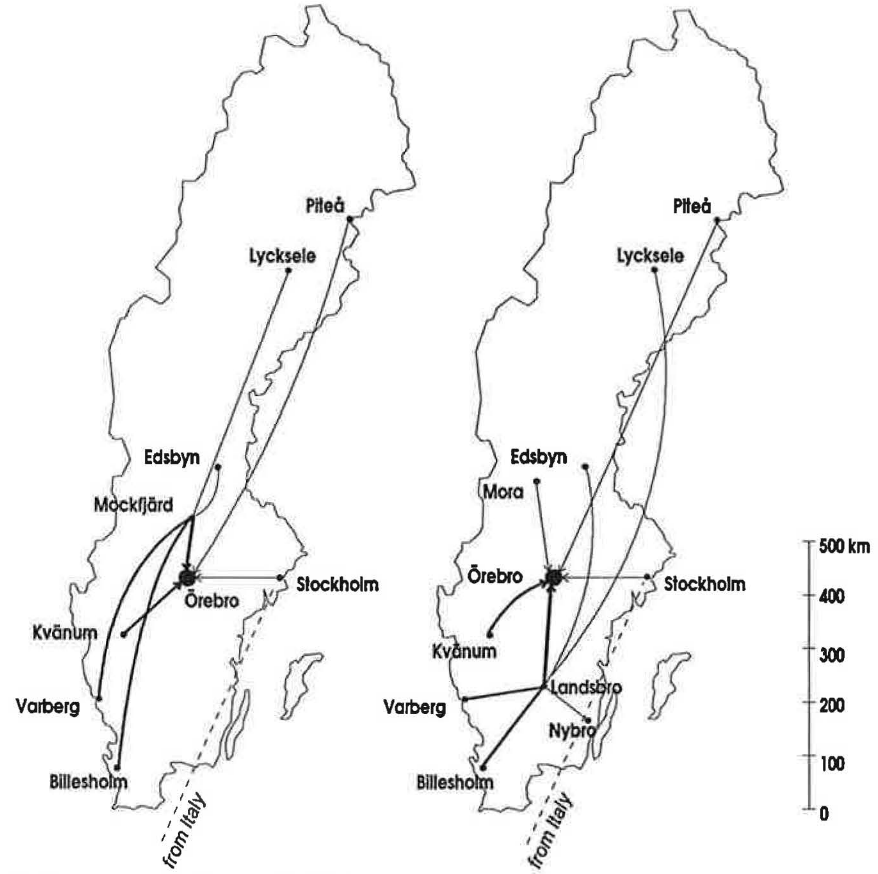

Fig. 10. The movement of transport with regard to construction materials for houses 1, 2 and 3. The map of Sweden on the left applies to house 1 and that on the right applies to houses 2 and 3. House 1 was prefabricated at Mockfjärd, and houses 2 and 3 were prefabricated at Landsbro. The building site of the three single-family dwellings is located 150 km west of Stockholm, in the city of Örebro. The thicker the lines in the figure, the greater is the share of the total energy required for transportation purposes. Only transportation requiring more than 50 kWh has been included.

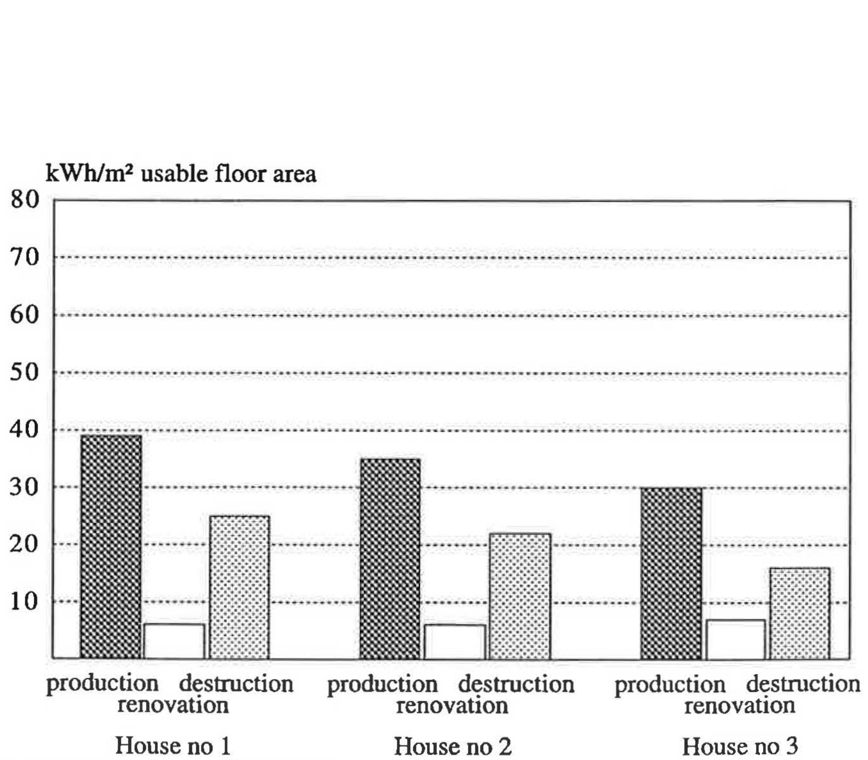

Fig. 11. Transport energy used in connection with production, renovation and destruction of the dwellings concerned.

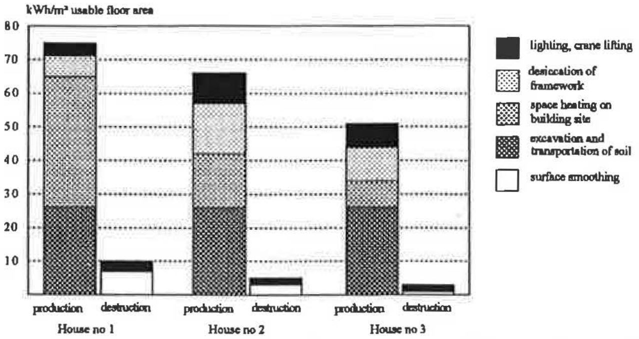

Fig. 12. Calculated energy use for various processes in connection with the erection and demolition of the three dwellings.

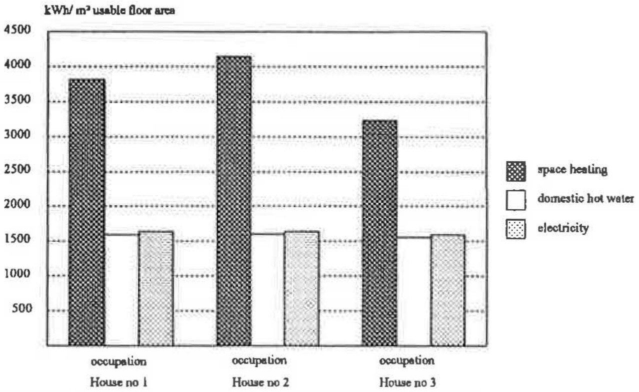

Fig. 13. Calculated energy requirements throughout the 50 years of occupation.

Table 2. Calculated energy use during occupation for space heating, hot water and electricity

	House 1 (kWh/m² yr)	House 2 (kWh/m² yr)	House 3 (kWh/m² yr)
Space heating, ventilation included	76	83	64
Domestic hot water	32	32	32
Electricity	32	33	32
Total	141	148	128

Table 3. Energy use during the life cycle of the three dwellings studied

Phases	House 1 (kWh/m² · 50 yr)	%	House 2 (kWh/m² · 50 yr)	%	House 3 (kWh/m² · 50 yr)	%
Production						
Manufacturing	900	11	870	100	730	10
Transportation	40	0	40	0	30	0
Erection	80	1	70	1	50	1
Management						
Occupation	7100	83	7400	85	6400	85
Renovation: manufacturing	390	5	370	4	330	4
Renovation: transportation	<10	0	<10	0	<10	0
Destruction						
Demolition	10	0	<10	0	<10	0
Removal: transportation	30	0	20	0	20	0
Total energy (kWh/m² · 50 yr)	8500	100	8800	100	7600	100

and electricity amounts to 141, 148 and 128 kWh/(m^2 usable floor area · year) for houses 1, 2 and 3, respectively. House 3 needs less energy for heating than the others; this is because it is a two-storey dwelling with smaller transmission losses (the other two are bungalows) and a lower air-change rate than houses 1 and 2.

Figure 13 presents the energy use of the dwellings during their occupation, calculated on the basis of a 50-year life-span. In fact, these energy usages have been calculated twice. The first calculation was based on planning documents. The second (shown in Table 2) was performed against the background of certain knowledge of how the dwellings were actually built, as there were deviations from the planning documents (the erection of the dwellings did not entirely comply with the drawings and designs). The heating requirement of the three buildings increased by, on average, 10%.

A further comparison has been made with the energy requirements measured in the dwellings [6]. Results from this comparison show that the energy requirements that were in fact registered are, by and large, even higher than those that were calculated on a theoretical basis.

SUMMARY AND CONCLUSIONS

Table 3 presents the total energy use of the three single-unit dwellings, "from the cradle to the grave". The results are presented as kWh/(m^2 usable floor area · 50 years). This table clearly shows that houses 1, 2 and 3 require 8500, 8800 and 7600 kWh/(m^2 usable floor area · 50 years) during their respective life cycle. Calculated on an annual basis, this works out at 170, 176 and 151 kWh/(m^2 usable floor area · year), respectively. The annual energy use for space heating, hot water and electricity amounts to 141, 148 and 128 kWh/(m^2 usable floor area · year), respectively, for the three dwellings. This means that some 85% of the total energy usage is required during the management phase — a significant finding. The conclusion at this point is as follows: in order to save energy it is essential to produce dwellings that require small amounts of energy during their management phases.

It should be pointed out that the three dwellings may, at present, be regarded as low-energy buildings. Thus, for instance, the energy use for space heating and ventilation only amounts to 76, 83 and 64 kWh/(m^2 usable floor area · year), respectively.

Table 3 also shows that the energy used in manufacturing all the construction materials employed in connection with the erection and renovation of the individual dwelling amounts to some 15% of the total energy use. This corresponds to some 7 years of occupation (space heating, hot water and electricity).

Another interesting observation is that the energy required for manufacturing heat-insulating materials for the dwellings (mineral wool and polystyrene) corresponds to less than 2 years' energy use during actual occupation (for space heating, hot water and electricity) (see Table 4). Such a low energy requirement for insulating material is noteworthy in view of the fact that these single-unit dwellings are, after all, low-energy houses.

Furthermore, Table 3 shows that the transportation and process energy used during the erection and demo-

Table 4. Energy requirements for manufacturing the materials used in insulating the dwellings. In addition, the table compares the energy use for manufacturing the insulating materials and the energy use during occupation (space heating, hot water and electricity)

	House 1, 130 m^2 usable floor area		House 2, 129 m^2 usable floor area		House 3, 138 m^2 usable floor area	
	Quantity (ton)	Energy for manufacturing (kWh/ton)	Quantity (ton)	Energy for manufacturing (kWh/ton)	Quantity (ton)	Energy for manufacturing (kWh/ton)
Polystyrene, manufacturing energy = 29 650 kWh/ton	0.66	19 570	0.65	19 270	0.33	9780
Mineral wool, manufacturing energy = 5330 kWh/ton	2.09	11 150	2.09	11 150	1.65	8800
Total energy used for the manufacture of insulating materials	30 700 kWh (236 kWh/m^2)		30 400 kWh (236 kWh/m^2)		18 600 kWh (135 kWh/m^2)	
Energy used during occupation (heating, hot water and electricity)	141 kWh/(m^2 yr)		148 kWh/(m^2 yr)		128 kWh/(m^2 yr)	
Relationship between the energy used for manufacturing construction materials and that used for occupation	1.70		1.60		1.10	

lition of the dwellings comprises approximately 1% of the total energy requirement. Thus, against the background of the entire life cycle of the single-unit dwelling, very little energy is used for such purposes.

As described above, the dwellings were prefabricated in factories for further transportation to the building site. This entails an "extra" transportation requirement compared to the situation where a dwelling is erected on the site "from scratch". Even so, these extra transportation requirements do not result in any significantly increased use of energy compared to the total energy requirement. In comparison to construction which takes place entirely on site, the advantages inherent in prefabrication outweigh the disadvantages. Thus, for instance, construction materials are protected from wind and weather; measurments are more exact; less material is wasted because prefabrication factories are in the habit of saving materials in order to save money; construction workers in charge of different stages in the building process have greater experience of their particular jobs, which means that construction elements will be better executed and combined; and so on.

RECOMMENDATIONS

By way of conclusion, three important recommendations may be articulated on the basis of this study.

1. Make sure the dwelling requires little energy during the occupation stage.
2. Monitor and follow up the building stage (the actual erection of the building) in order to ensure quality in the construction work.
3. Select construction materials whose manufacture requires little energy.

If these three points, in the order stated, are adhered to, the outcome will be an energy-efficient single-unit dwelling throughout its life cycle.

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