HÖGSKOLEPROJEKT II: EVALUATION OF EFFECTS OF ENERGY-CONSERVATION RETROFITS IN EXISTING RESIDENTIAL BUILDINGS

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ABSTRACT

This paper is a summary of a report of a pre-study from the HII group*. It concerns 45 retrofitted buildings for which post retrofit measurements were made during the winter of 1983/84.

In the existing energy conservation plan from the Swedish government estimates of the energy saving effect have been done by calculations for different retrofits. Before the conservation plan is reviewed, it is important to find out whether these estimates can still be used or should be changed.

The purpose of Högskoleprojekt II is to describe the average energy savings effect of a number of retrofits and how this effect varies from one building to another. Furthermore, studies will be made to explain variations in the energy-saving results. Great variations were observed in the preceding investigation, "Högskoleprojekt I". The attempt to explain such variations in saving effect is meant to form the basis for recommendations about how retrofits shall be performed practically to achieve the greatest possible savings.

The investigation is carried out by three institutes of technology, the Northern Swedish Building Centre, and the Swedish Building Research Institute. The investigation is a before/after study of buildings in which energy conservation retrofits were carried out with governmental support during 1983 and 1984. Approximately 375 buildings are included in the investigation. There are both single-family and multifamily (about 200) houses situated in four different parts of Sweden. Continuous weekly measurements of energy consumption before and after retrofit are done. Furthermore, the indoor and outdoor temperatures are measured simultaneously. In addition weekly measurements of insolation and wind speed were obtained from the Swedish Meteorological and Hydrological Institute.

The most common retrofits in the investigation are (1) the "retrofitpackage" which consists of both structural and mechanical retrofits (multifamily houses) and (2) conversion from oilheating to heating with a heatpump (both multifamily and single-family houses). A special calculation model has been developed and is to be evaluated within the project. "After"measurements were carried out in most of the houses during the winter of 1984/85.

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INTRODUCTION

Swedish governmental support for energy saving retrofits in residential buildings has been offered since 1974. The support has been given as loans and grants. A great number of retrofits, both structural and mechanical, including many conversions from oil heating to another type of heating system, have been carried out. Different retrofits have been emphasized during different periods. It is important to examine whether particular retrofits carried out give sufficient energy savings, or if other retrofits, or combinations of retrofits ought to be given priority.

In the energy conservation plans of 1978 and 1981, the national goal for the reduction in yearly energy consumption of buildings between 1978 and 1988 was set at 48 TWh, with 43 TWh coming from residential and commercial buildings. It is important to see whether the estimates that form the basis for the conservation plans are accurate or if they have to be modified. A great number of investigations, casestudies, and statistical analyses have been and are beeing carried out to form a basis for any modifications.

The most extensive of the statistical investigations of average energy savings has been made within the Högskoleprojekt I and II, carried out as a cooperative project among the following institutions:

- Northern Swedish Building Centre, Umeå, together with the Division of Structural Engineering, University of Luleå
- Energy Conservation in Buildings Group. the Royal Institute of Technology, Stockholm
- Department of Building Technology, Chalmers University of Technology, Gothenburg
- Department of Building Science, Lund Institute of Technology, Lund
- Division of Energy Conservation, Swedish Building Research Institute, Gävle

Högskoleprojekt I was carried out between 1979 and 1981 and included about 1 000 single-family and multifamily houses in which different energy conservation retrofits were carried out with governmental support. The results from Högskoleprojekt I showed that considerable average energy savings were obtained in the retrofitted houses (Anderlind et al.) In the multifamily houses, the average actual saving from structural retrofits was greater than the theoretical saving. Installation of thermostatic radiator valves and heating control equipment also resulted in significant savings. In the single-family houses, either wall or attic insulation alone gave an average saving that was close to the expected one. Triple glazing gave an average energy saving slightly greater than the theoretical one. However, combinations of structural retrofits such as wall and attic insulation or wall insulation and triple glazing resulted in an energy saving that was only half the theoretical one. One explanation could be that a part of the potential energy saving is used for increasing the indoor temperature. There were great variations in energy savings between different buildings with the same retrofit.

The purpose of Högskoleprojekt II is, like Högskoleprojekt I, to describe the average saving effect of a number of energy-conservation retrofits and how the saving effect varies from one building to another. Another purpose is to explain these variations.

METHODOLOGY

The investigation is a before/after study of buildings which were retrofitted in 1983 (pre-study) and 1984 (mainstudy). In total about 375 houses were investigated, including a pre-study of about 50 houses. The investigation includes both multifamily and single-family houses. The number of houses investigated by the different institutions are: Umeå/Luleå, 92; Stockholm, 140; Gothenburg, 62; and Lund, 80. The houses are situated in seven different counties in Sweden, (see Figure 1).

Some important improvements in procedure have been made compared to Högskoleprojekt I. In that study, the indoor temperature was unknown and had to be assumed. Data on energy consumption were collected from home-owners or oil or power companies. It is possible that for some of the single-family houses, the data on energy consumption were either incomplete or incorrect.

In the ongoing project, the energy consumption and indoor and outdoor temperatures are measured carefully. Since the buildings was chosen among buildings where retrofits were going to be carried out (not as in Högskoleprojekt I among buildings where the retrofits had already been carried out) it has been possible this time to measure both before and after the retrofits. In addition, weekly measurements of insolation and wind speed were obtained from the Swedish Meteorological and Hydrological Institute. Therefore the investigation is carried out under more controlled conditions, and the results may be expected to be more exact than in Högskoleprojekt I.

Great variations in saving effect have been found in buildings in which the same retrofit or combinations of retrofits have been carried out.To attempt to explain these variations, follow-up studies will be made in a number of houses where especially great or small savings were achieved. One of the purposes of these studies is to come up with a basis for recommendations on how to improve the retrofits and the suitability of certain retrofits to certain types of buildings in order to to achieve the greatest possible savings.

At the reinspection, complimentary measurements will be made, and additional data about the building will be collected. The follow-up studies can be divided under seven different headings:

- transmission
- ventilation and air leakage
- heating equipment
- heat distribution and heat control
- occupant behavior
- energy use and climatic data
- retrofit

A large part of the follow-up studies will be analyses of the building data collected earlier. At the reinspections, the emphasis will be on the heating equipment and the retrofit(s).

The investigation includes a pre-study and a main study. Pre-retrofit measurements for the pre-study were carried out during the winter of 1982/83. Post-retrofit measurements were made during the winter 1983/84 when the pre-retrofit measurements for the mainstudy were also made. During the winter of 1984/85, post-retrofit measurements were made for the mainstudy and also a second post-retrofit- period for the pre-study. Analysis and follow-up studies will be made during 1985/86, and a final report is planned for after the summer 1986.

The investigated buildings were mainly chosen among those for which governmental support had been applied. Other buildings were chosen from a postal inquiry of about 3 000 private apartment building owners. Contacts with housing associations have also located a number of buildings. In order to isolate the effects of retrofits, strict rules and criteria were stipulated for the selection of the buildings.The rules and criteria are shown in Table 1.

A detailed inspection form and questionnaire were prepared and used to collect data about all the houses, mainly in terms of building construction and building services, and special inspection forms were prepared for every retrofit. Special microprocessor-based meters for temperature and oil consumption were developed for this investigation and for an investigation of energy consumption in 300 single-family and multifamily houses (Norlén 1985). Figure 2 shows the meters. At the on-site inspections, the meters were installed. Existing meters were used in houses heated by district heating, electricity and gas. Weekly readings of the meters were made. In most cases the home-owners made the readings and then sent the data to the institutions.

The length of the measuring period should be at least 12 weeks, and the measurements should be made during the same time of year both before and after retrofit. For most of the houses, the measuring period was between December and April. During the summer, special measurements of the "summer consumption" have been made. The measuring period for the houses where heatpumps had been installed is a whole year after retrofit; this is because of the special method of analysis used. In the multifamily houses, the temperature was measured in one apartment throughout the whole test period. In addition, the temperature was measured in three other apartments for a shorter time period.

RETROFITS

The retrofits chosen for the study had to fulfil one or more of the following conditions:

1. It was common among houses in Sweden.
2. It was expected to result in a great saving of energy.
3. It had unknown economic value.
4. It gave inconclusive results in the preceding investigation (Högskoleprojekt I).
5. It was expected to give results different from earlier studies.
6. It should be a candidate for present or future subsidies.

An important consideration in the choice of retrofits was that a sufficient number of buildings with the same retrofit could be found so that a representative result could be produced.

The following retrofits were chosen for the study

Multifamily houses	Number
retrofit package	52
additional insulation of attic	34
heat pump	25
district heating	38
triple glazing	33
regulating package	20

Single-family houses	
ground-source heat pump	39
outdoor air-source heat pump	36
conversion to electric heating	40
insulation package	27
retrofit package	6
triple glazing	21
additional insulation of wall	3

The retrofit package is defined as at least three retrofits carried out in the building, including at least one big structural retrofit and one big mechanical retrofit. The regulating package is defined as installation of thermostatic radiator valves and adjustment of the heating system. Installation of heating control equipment and adjustment of the ventilation system can also be included. The insulation package is defined as at least two big insulation retrofits carried out in the building. For the retrofits chosen for the pre-study see "Result" section.

CALCULATION MODEL

The calculation model used is based on the assumption that the weekly energy consumption for space heating and domestic hot water in a building is linear in the weekly average indoor/outdoor temperature difference during the heating season and is independent of temperature during the nonheating season. On the basis of these assumptions, the energy signature of a building can be determined from weekly measurements of energy consumption and temperature. The equation of the energy signature is determined by the least-squares method. The slope of the fit is the heat loss factor of the building, i.e., the amount of increase in energy consumption for a one-degree Celsius increase in the indoor/outdoor temperature difference. The intercept - the "energy consumption" at zero indoor/outdoor temperature difference - is the winter factor. Similarly, the summer factor is defined as the average nonheating energy consumption. The energy signature is shown in Figure 3. The consumption of the building for an average year is given by:

$$W = bQ + cT + dP \qquad 1)$$

where

- W = he annual energy consumption per apartment or per m^2 for the average year (kWh/yr·apartment or kWh/yr·m^2)
- Q = the number of degree hours, to the base temperature of the individual dwelling, during the average year (^oC)
- T = the length of the heating season in the average year (h)
- P = the length of the nonheating season in the average year (h)
- b = the loss factor of the building, as found from the least-squares fit (kWh/h·apartment·^oC or kWh/h·m^2·^oC)
- c = the winter factor, as found from the least-squares fit, (kWh/h·apartment or kWh/h·m^2)
- d = the summer factor for the building (kWh/h·apartment or kWh/h·m^2)

For the average year, the number of degree-hours, Q, and the length of the heating season, T (and thus also the length of the nonheating season, P), are determined from outdoor temperature data for the place where the house is located, measured indoor temperature, and an estimated critical temperature difference - the indoor/outdoor temperature difference at which operation of the space heating equipment starts and stops. For the analysis presented in this paper, we have used a fixed value of 10 ^oC for this critical temperature. Handbook values are used for the summer factor.

In electrically heated houses, where household energy consumption is included in the metered space-heating consumption, we used handbook values of household energy consumption to find the space-heating consumption alone. Handbook values were also used in cases where the domestic hot water consumption was not included in the energy measurement. The energy consumption is normalized for both the pre- and post-retrofit periods, and the energy saving is calculated as being the difference between these two normalized values.

The model described above has been used for the pre-study and for the results given in this paper. However, for the final analysis, which will cover all the buildings in the study, a more sophisticated version of this model will be employed. One of the advantages of the final model will be the inclusion of insolation in the analysis. Another advantage is that measured values for the summer factor will be used for each building.

For those buildings where heat pumps were installed, the model described above was not used. Because the coefficient of performance (COP) of a heat pump varies with outdoor temperature, the linear relationship between energy consumption and indoor/outdoor temperature difference is unlikely to hold true. Since we do not know the relationship between energy consumption and climatic load, we cannot normalize to a standard year. Instead, we estimated what the energy consumption would have been if the retrofit had not taken place. We compared the actual energy consumption, Wep, during the test period with the energy consumption estimated using weather data for the test period and the energy signature calculated from pre-retrofit period.

$$W'_{ep} = (b_f \Delta_E + c_f) \cdot T_E \qquad 2)$$

where

W'_{ep} = the estimated energy consumption without retrofit (kWh/apartment or kWh/m2)

b_f = the heat loss factor before retrofit (kWh/h·apartment·°C or kWh/h·m²·°C)

Δ_E = the post-retrofit average temperature difference (°C)

c_f = the winter factor before retrofit (kWh/h·apartment or kWh/h·m²)

T_E = the length of the post-retrofit period (h)

The difference in energy consumption is expressed as a percentage,

$$(W_{ep} - W'_{ep})*100/Wep. \qquad 3)$$

where

W_{ep} = the measured energy consumption after retrofit (kWh/apartment or kWh/m²)

Since the linear energy signature method cannot be used for heat pumps, the measuring period has been extended to one year for those buildings, with readings being taken monthly. The measurements will also include a test period during which readings are taken weekly, just as for all the other buildings. In the final report, the complete year's measurements will be used to calculate energy savings.

RESULTS

The analysis of the measurements that were taken during the winter of 1984/85 is not yet complete. Thus the results presented in this paper are taken from the pre-study. The measured indoor temperature was used to find the length of the heating season and the number of degree days. Thus the energy savings include the effect of any changes in indoor temperature between the pre- and post-retrofit periods. In the pre-study, pre- and post- measurements were made on 45 buildings. The retrofits investigated can be divided into the following groups:

Retrofit package	-	Multifamily	14	buildings
Attic insulation	-	"	8	"
Heat pump	-	Single-family	10	"
Conversion to electric heating	-	"	9	"
Triple glazing	-	"	2	"
Wall insulation	-	"	2	"

Retrofit Package

The most common retrofits in this group were installation of attic insulation and thermostatic radiator valves, and adjustment of the heating system. Details of the retrofits carried out on individual buildings are given in Table 2. Energy consumption decreased in 12 of the 14 buildings and increased slightly in two. There was great variation among buildings, with savings from 72 $kWh/m^2 \cdot yr$ to an increase of 6 $kWh/m^2 \cdot yr$. The average pre-retrofit consumption was 206 $kWh/m^2 \cdot yr$, and the post-retrofit consumption was 184 $kWh/m^2 \cdot yr$, that is decrease of 22 $kWh/m^2 \cdot yr$, or 11 %. The greatest changes were seen in those buildings with a high pre-retrofit consumption, as seen in Table 2.

Attic Insulation

For the multifamily buildings in which the retrofit was attic insulation only, energy consumption decreased in six buildings and remained unchanged in two. The average pre-retrofit consumption was 220 $kWh/m^2 \cdot yr$, and the post retrofit value, 206 $kWh/m^2 \cdot yr$, a saving of 14 $kWh/m^2 \cdot yr$, or 6%. Even in these buildings, the variation in savings between individual buildings was rather large, varying from 0 to 38 $kWh/m^2 \cdot yr$. In this group too, the greatest savings were observed in those buildings that had the largest pre-retrofit consumption, (for details, see Table 3). One of the reasons that attic insulation was chosen as a retrofit was that in the Högskoleprojekt I, this retrofit gave much larger savings than predicted. Theoretical calculations have not yet been carried out for the buildings in this study, so no such comparison has yet been performed.

Heat Pumps

A large number of heat pumps have been installed in Sweden, with the expectation that they would give great savings. For this reason it was important to include this type of retrofit in the study. The main study includes a group of multifamily houses with different types of heat pumps, and two groups of single family houses, one with ground-source heat pumps and the other with outdoor air-source heat pumps. The results from the pre-study concern five groundwater units, four shallow-ground-source units, and one outdoor air-source unit, all single-family houses. Using the calculation method described above, we found that the savings varied from 46% to 71%, with an average of 58% (for details, see Table 4.) For these installations was a coefficient of performance also calculated (COP), defined as the net energy that would have been consumed by the building had the retrofit not been performed (calculated from the energy signature) divided by the actual energy consumed by the heat pump during the measuring period. The COP varied between 1.2 and 2.3, with an average of 1.6.

Conversion to Electric Heating

Nine conversions in single family house were included in the pre- study. There were two kinds of retrofits, the "Elkassett," an electric resistance boiler in the existing hydronic heating circuit, and the "Elpanna," a rather larger electric resistance boiler. Four "Elpannor" were installed and five "Elkassetter." Before retrofit all nine buildings were oil heated. On average, the energy consumption decreased from 41.2 to 32.5 MWh/yr, a decrease of 8.7 MWh/yr, or 21% (see Table 5).

Wall Insulation and Triple Glazing

In a few single-family houses structural retrofits are studied. The energy consumption decreased in both buildings where wall insulation was carried out. In the two buildings where triple glazing was done, energy consumption decreased in one and increased in the other.(see Table 6).

Indoor Temperatures

No trace of systematic changes of indoor temperature was found in the pre-study. In the 45 buildings studied, the temperature increased in about half and decreased in about half. The average indoor temperature in multifamily houses was approximately 22.1 $^{\circ}C$ and it was 20.8 $^{\circ}C$ in the single-family houses (see Table 7). This difference in indoor temperature between multifamily and single-family houses was also observed in an earlier investigation (Holgersson and Norlén 1982).

CONCLUSION

The following conclusions were made from the pre-study.

A noticeable average energy saving has been obtained in the retrofitted buildings, but great variations were seen between different buildings.

The retrofit-package in the multifamily houses gave an average energy saving of 11%. The greatest savings were seen in those buildings with high pre-retrofit consumption.

In multifamily houses where attic insulation was done the average energy consumption decreased by 6%. The savings variated a lot from one building to another - ranging from 0 to 38 KWh/m^2 yr. As in the retrofit-package group, buildings with high pre-retrofit energy consumption obtained the greatest energy savings.

Installation of heat pumps in single-family houses gave a calculated average energy saving of 58% with variation between 46% and 71%.

In single-family houses where conversion to electric heating from oilheating was carried out, the energy consumption decreased by between 0% and 40% with an average decrease of 21%.

The average indoor temperature in multifamily houses was approximately 22.1 ^{o}C, and it was 20.8 ^{o}C in single-family houses.

It should be noted that these results were obtained from a small sample of only 45 buildings so it is not possible to draw any definitive conclusions. That must await the results of the main study.

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TABLE 1

Criteria for Selecting Buildings for the Investigation

The following criteria applied when determining whether a building, as selected, should be included in the study or not.

1. The volume heated to more than 18 ^{o}C (room temperature) must not have been altered by rebuilding or additions between pre- and post-period

2. For single-family houses: the house must not have changed its owner/household between pre- and post-period. The house must also have been continously occupied.

3. For single-family houses: the house must be a detached single-family house or linked house and not a two-family, semidetached, or terraced house.

4. For multifamily houses: the building must have at least five apartments

5. At least 75% of the floor area must be used for residential purposes.

6. The building must have some source of heat that can be metered.

7. If the building shares its heat source with other buildings, there must be separate metering of heat consumption.

8. If the building is heated by district heating, there must be an energy meter, not merely a flowmeter.

9. No additional heating that cannot be metered must have been used.

10. No energy conservation measure than those involved in the investigation may have been carried out. Allowance must be made for any other reasons for changes in building energy consumption.

TABLE 2
Measured Normalized Energy Saving in 14 multifamily Houses Where Retrofit-package Has Been Carried Out

The houses are listed according to energy consumption before retrofit

Retrofit No. 12345678910	Building No.	Number of apartments	Heated area/ apt.	Number of storys	Energy consumption (KWh/m^2, year) before	after	saving
23 567	701	8	61	3	308	236	-72
1 5 78	506	35	78	3	260	223	-37
1 45 7 910	504	112	95	9	259	204	-55
1 45 10	502	38	77	3,5	251	208	-43
12 5 78	507	36	92	3	240	227	-13
1 7 10	102	52	74	3,5	218	204	-14
1 45 7	508	28	90	4	211	208	- 3
1 45 10	501	73	90	3	193	188	- 5
1 5 7	103	78	80	3	192	164	-28
1 5 7	101	2	104	4	173	174	+ 1
3 5 78	314	14	63	3	162	158	- 4
3 5 78	318	19	84	3	157	136	-21
3 5 78	316	21	79	3	134	123	-11
3 5 78	320	14	87	3	119	125	+6

Retrofit numbering:

1 Attic insulation
2 Wall insulation
3 Triple glazed windows
4 Weather stripping
5 Thermostatic valves
6 Aquastat/heat regulation regulation equipment
7 Adjustment, heat distribution
8 Adjustment, ventilation
9 Exhaust air heat pump
10 New burner and/or boiler

TABLE 3

Measured Normalized Energy Saving in 8 Multifamily Houses Where Attic Insulation was done

The houses are listed according to energy consumption before retrofit.

Retrofit No	Number of apartments	Heated area/ apt.	Number of storys	Energy Consumption (KWh/m^2, year) before	after	saving
511	12	63	3	322	292	-30
515	35	74	3	288	250	-38
104	17	70	4	250	241	- 9
105	16	96	5	224	210	-14
514	57	89	3	192	178	-14
512	36	91	4	181	181	0
513	36	91	4	174	170	-4
516	148	95	7	128	128	0

TABLE 4

Measured Normalized Energy Saving in 10 single-family Houses Where Heat Pumps were installed.

The houses are listed according to energy consumption before retrofit

Type of heat pump	House No.	Heated Area	Energy consump. before retrofit MWh/year	Postperiod length (weeks)	outdoor temp.	Rel coeff. of perf.	energy saving %
Ground-water	404	404	101,0	15	1,5	1,7	-62
Ground-water	402	225	82,3	19	0,5	1,3	-49
Ground-water	206	337	73,1	11	5,2	2,0	-67
Shallow ground	406	293	70,0	10	3,0	1,3	-49
Ground-water	401	252	49,9	12	-2,4	2,3	-71
Shallow ground	605	257	47,4	13	-3,0	1,6	-59
Shallow ground	6	250	46,2	14	2,9	1,5	-57
Ground-water	604	242	39,4	11	0,5	2,1	-68
Outdoor air	3	181	36,5	14	3,9	1,2	-46
Shallow ground	7	139	35,5	14	2,9	1,4	-52

TABLE 5

Measured Normalized Energy Saving in 9 Single-family Houses Where Elpanna or Elkassett Have Been Installed

The houses are listed according to energy consumption before retrofit. The consumption of oil during the pre-period has been converted into kWh, using the conversion factor 9,935

Retrofit	House No	Heated area	Energy consumption MWh/year Before	After	Saving
Elpanna	821	288	62,7	41,9	-20,8
Elkassett	603	190	45,8	27,4	-18,4
Elkassett	601	232	41,0	32,4	- 8,6
Elpanna	607	180	40,9	28,7	-12,2
Elpanna	823	240	38,6	33,1	- 5,5
Elpanna	822	243	37,4	35,9	- 1,5
Elkassett	843	163	35,9	35,9	0
Elkassett	841	239	35,0	32,8	- 2,2
Elpanna	606	125	33,7	24,3	- 9,4

TABLE 6

Measured Normalized Energy Saving in 4 Single-family Houses Where Wall Insulation or Triple Glazing Has Been Done

Retrofit	House No.	Heated area	Energy consumption MWh/year Before	After	Saving
Wall insulation	4	121	31,2	24,7	- 6,5
Wall insulation	5	106	27,8	17,6	-10,2
Triple glazing	201	264	27,3	20,4	- 6,9
Triple glazing	204	255	26,0	27,9	+ 1,9

TABLE 7

Average Indoor Temperatures Before and After Retrofit in Multifamily and Single-family Houses

Type of house	Number of houses	Indoor temperature oC before retrofit	after retrofit
Multifamily house	22	22,2	22,0
Single-Family house	23	20,8	20,8

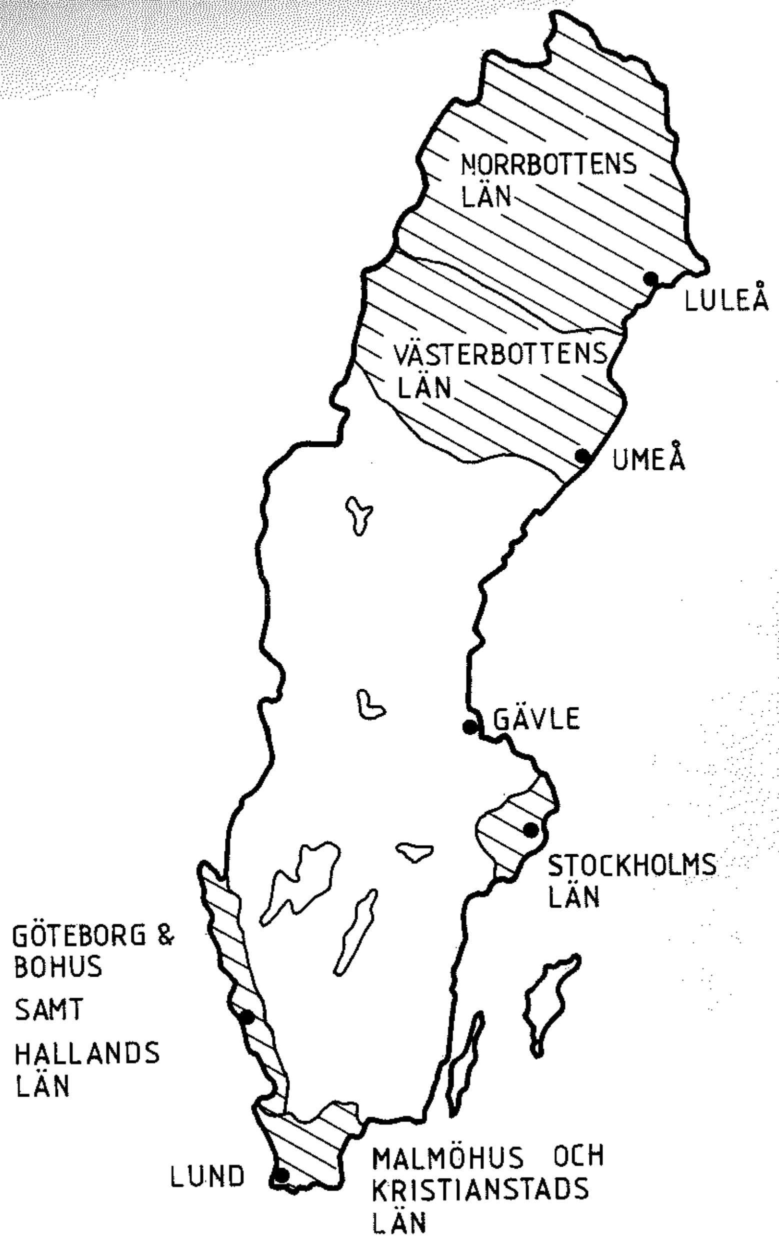


Figure 1. Map of Sweden showing seven counties studied in this investigation

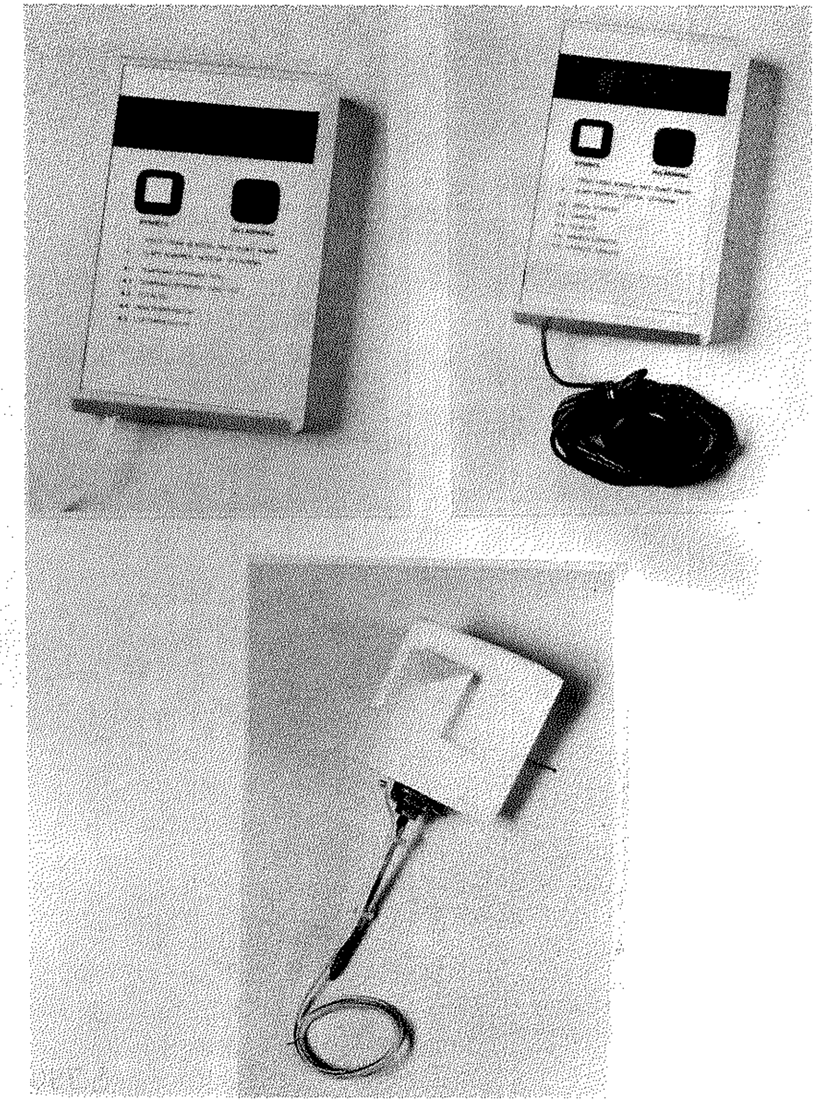
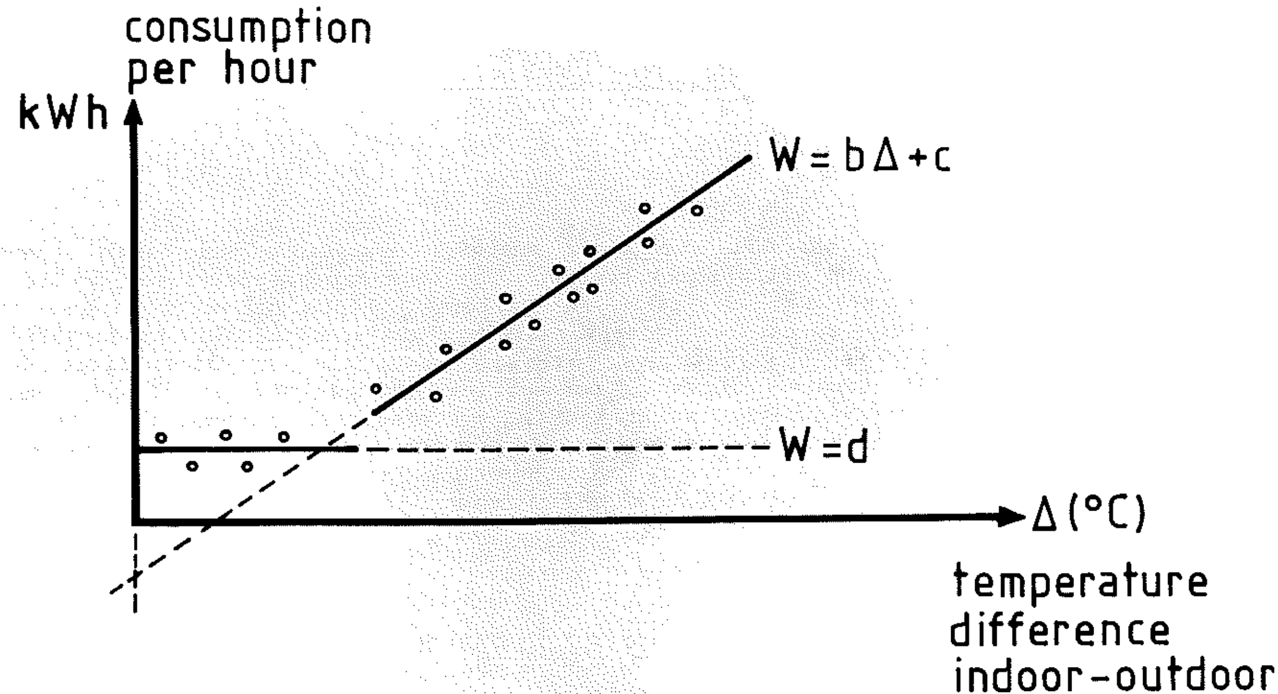


Figure 2. Electronic measurement instruments used in investigation

ENERGY SIGNATURE



$W = bQ + cT + dP$

b = loss factor
c = winter factor
d = summer factor

Figure 3. Relation between energy consumption per time unit and difference between indoor and outdoor temperature