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Energy efficiency—a forgotten goal in the Swedish building sector?

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Abstract

The paper analyses trends in energy use and carbon dioxide emissions in the Swedish building sector between 1970 and 2000 with focus on the development of energy efficiency in the average stock of buildings and in the new construction. The energy efficiency improved throughout the seventies and early eighties, and studies revealed major potentials for further improvements. However, the energy efficiency has levelled off with almost no improvement during the nineties. The statistics for new-constructed multi-dwelling buildings indicate increasing energy use per floor area since 1995, and even more amazing: the new-constructed multi-dwelling buildings are at the same level of energy efficiency as the average existing building. Parallel to this development, the best available technology represented by low-energy buildings, uses less than a third of the energy used in average new buildings. Much of this development may be explained by changes in energy prices. The increasing oil price between 1972 and 1985 correlates well with the improvements in energy efficiency, even though the effect was limited by the low electricity price following the nuclear power programme. However, promotion of energy efficiency is complicated by the ineffective distribution of costs and benefits between actors, especially in the new construction. Moreover, to the residents energy cost is a small part of the expenditures and energy efficiency is merely one of many qualities valued in a building. An important factor behind the increasing energy use in new-constructed multi-dwelling buildings may also be new exceptions in the energy standards which were introduced to promote district heating. Finally, the paper gives some policy recommendations to improve the energy efficiency in the Swedish building sector: Not to support supply substitution at the expense of energy efficiency; Regulations for individual measurements and debiting of space and water heating; Strengthening of the energy standards to promote technical efficiency in the new construction.

Keywords: Energy efficiency; Carbon dioxide emissions; Building sector

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1. Introduction

The energy system plays a central role in the interrelated economic, social and environmental aims of sustainable human development (WCED, 1987). It is clear that the present energy system must be transformed on the supply side as well as on the conversion and use side in order to fulfil sustainability criteria. The discussion of future sustainable energy systems has a tendency to focus on the supply side even if energy efficiency is the dominant factor in most energy scenarios. In the scenarios developed by IIASA-WEC, the global energy intensity (energy per GDP) is presumed to decline by 0.8–1.5 per cent a year until 2100 (WEA, 2000). In an energy scenario developed by Azar (2003), the amount of negawatts (energy efficiency) equals the total supply of energy year 2100, which corresponds to 0.7 per cent annual increase of energy efficiency during the 21st century.

If energy efficiency is presumed to play such an important role in the future energy system, it is important to learn from history. Have earlier presumptions of improved energy efficiency come true or not? Why or why not?

In Sweden, a series of future studies within the energy field were carried out from 1974 and onwards. In this series, a future study on energy efficiency entitled "Energy—for what and how much?" was published in 1981 (Steen et al., 1981). This study was not a forecast. The aim was instead to give some consistent future scenarios, which illustrate some of the available options. The study used two levels of technologies: "present known best technology" which was cost effective with existing energy prices, and "advanced technology" which was presumed to become cost effective within a period of 20–30 years. Since the study took its departure in 1975, it is now time to compare the result with the actual situation, see Fig. 1. In the figure, the

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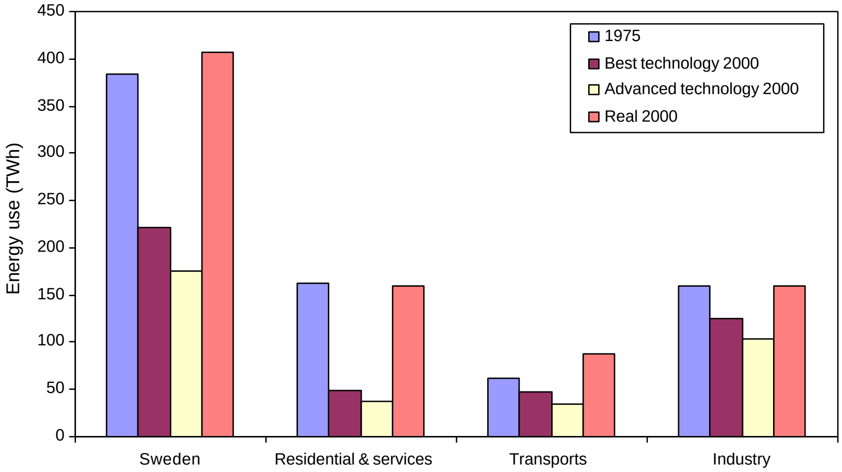

Fig. 1. A comparison between the actual energy use (delivered energy) in 1975 and 2000 and the scenarios for the year 2000 in Steen et al. (1981).

presumption of the increase of economic activity was slightly higher than the actual situation. Still, it is clear that the energy use did not decrease as much as it could according to the study. This is especially true for the building sector.

International comparisons also indicate that the energy efficiency of the Swedish residential sector is improving slowly. With time series from 1970 to 1983, Schipper et al. (1985) held up Sweden as a model country for energy-wise housing. Extended time series to 1995 in Schipper et al. (2001), however indicates that other countries are catching up and that some are passing Sweden in energy efficiency. It was shown that the indicator *useful space heating energy per floor area and degree-day*, was about 25 per cent higher in the USA than in Sweden in the mid-seventies. However, unlike for Sweden where the efficiency improvements stagnated in the eighties, the US efficiency continued to improve and reached the Swedish level in 1989. In 1995, the indicator was already more than 10 per cent lower for the USA.

The residential and service sector represents around 40 per cent of the total energy use in Sweden. It had and still has great potential for improved energy efficiency, but the total energy use in this sector has remained almost unchanged since 1975. Why? What can we learn for the future?

In order to answer these questions, it is necessary to study the energy use in the residential and service sector more thoroughly. This has previously been done in several studies by, e.g. Schipper et al. (1985, 1994, 1997, 2001), Schipper and Price (1994) and in reports from the Swedish Council for Building Research, such as BFR (1984) and Carlsson (1992). The latter describes energy use in buildings between 1970 and 1990 in great detail, which has been important as a data source for the earliest period of this study. A report by the Swedish Energy Agency (2000) also gives a retrospective view of the development of energy efficiency in different sectors. Schaefer et al. (2000) further assessed the effectiveness of different policy measures for residential heating looking at five European countries, including Sweden.

The aim of this study is to analyse the development of energy efficiency in the Swedish building sector during the last 30 years, and to assess its importance for reducing carbon dioxide emissions. We also take one step further in quantifying the importance of various technical factors for efficiency development in the past. The focus is on technical change, but we also discuss the underlying driving forces of this development.

In the next section, we will describe the method that has been used in our study. The following section presents the results and in the final sections conclusions are drawn and discussed.

2. Methodology

2.1. Factorisation and decomposition method

The analysis is based on an approach in which the carbon dioxide emissions from energy use U_t are expressed as a product of time-dependent factors $B_{t,i}$ (Eq. (1))

$$U_t \equiv \prod_i B_{t,i} \tag{1}$$

An additive decomposition method is applied in order to illustrate the contribution of each factor for changing total emissions between 2 years ΔU_i. This approximation generates a residual term $\Delta U_{residual}$ (Eq. (2))

$$\Delta U = \sum_i \Delta U_i + \Delta U_{residual} \tag{2}$$

Using the Parametric Divisia Method (see, e.g. Ang, 1995), the terms ΔU_i can be expressed as shown in Eq. (3)

$$\Delta U_i = (U_0 + \alpha(U_t - U_0)) \ln \frac{B_{t,i}}{B_{0,i}} \tag{3}$$

The parameter α is a constant between 0 and 1 where a value of 0.5 gives equal weight to both years. The choice of α affects the absolute values of the parameters ΔU_i but not their relative relation. We selected α with the objective to minimise $\Delta U_{residual}$.

In this study, five factors $B_{t,i}$ (Eq. (1)) have been identified.[1] The specific expression of U_t is given in Eq. (4)

$$U_t \equiv \frac{U_t}{E_{prim,t}} \frac{E_{prim,t}}{E_{del,t}} \frac{E_{del,t}}{A_t} \frac{A_t}{R_t} R_t \tag{4}$$

where E_{prim} is primary energy, E_{del} delivered energy, A heated floor area, and R the number of residents.

2.2. *Definitions and data assumptions*

2.2.1. *Residents*

The population has been divided into residents of one- and two-dwelling buildings and multi-dwelling buildings based on data from Statistics Sweden's Living Conditions Survey (ULF).

2.2.2. *Floor areas*

The total heated floor area is divided in three groups of buildings: (1) one- and two-dwelling buildings including row houses, (2) multi-dwelling buildings, and (3) non-residential buildings, which include both public and commercial buildings but not industrial buildings.

The energy statistics from Statistics Sweden (series EN16) cover the years between 1978 and 2000. There is however a significant lack of consistency in the figures for heated floor areas and thus these data cannot be used directly for time-series purposes. The most important feature for our purpose is that the relative changes are correct.

We chose the year 2000 as the starting point with 257 Mm^2 for one- and two-dwelling buildings and 168 Mm^2 for multi-dwelling buildings. An exception was made for non-residential premises as the statistics for 2000 is 7 per cent higher than both 1999 and 2001. Linear interpolation gives 158 Mm^2 for 2000. Time series were established by correcting figures backwards for changing definitions in the statistics. Between 1970 and 1977, estimates from Carlsson (1992) were used.

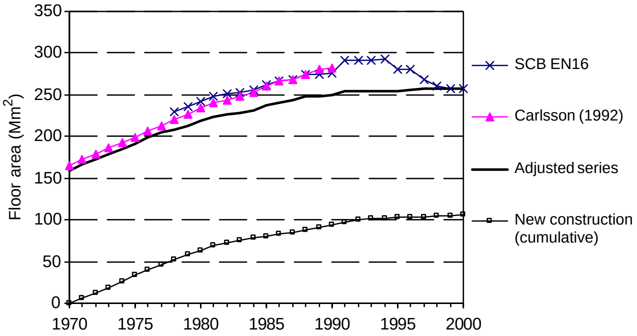

Fig. 2. Statistics of heated floor areas for one- and two-dwelling buildings in million square metres (Mm^2).

The time series for one- and two-dwelling buildings are the least consistent. For example, the raw data on heated floor areas indicate a reduction from 292 Mm^2 in 1994 to 257 Mm^2 in 2000 due to changing definitions. Raw data from Statistics Sweden and Carlsson (1992) are presented together with our adjusted data series in Fig. 2. The trend fits well with the statistics for new construction.

2.2.3. *Delivered energy*

The residential energy data from Statistics Sweden are provided in delivered energy. This means energy paid for by the consumers and supplied to the buildings, which includes losses within buildings but not external conversion and transformation losses. Changing from decentralised oil furnaces to centralised oil-fired district heating production may thus increase the efficiency at the point of delivery whereas the total use of oil could remain unchanged.

Energy use is divided in two groups of end-use services: (1) space and water heating including electric heating, and (2) electricity for non-heating purposes such as powering of appliances and lighting. The existing statistics does not support a separation of space heating from water heating.

As for floor areas, the main source of data on space and water heating is Statistics Sweden's series EN 16 "Summary of energy statistics for dwellings and non-residential premises". For the seventies, all data are taken from Carlsson (1992). These two data series fit well in the overlapping period between 1978 and 1990.

For data on the energy intensity in the new construction, Statistics Sweden carried out separate data extractions from their 2001 databases, to supply energy intensity against year of completion (1970–1999 for 2000 and 1970–2000 for 2001). This gives on average 80 observations per year for one- and two-dwelling buildings and 110 observations per year for multi-dwelling buildings (one observation may include more than one building). As the number of observations in each year depend on the total number of buildings erected that year, the low rate of new construction

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[1] The identification of factors is a compromise between the aim to describe the development in a detailed manner and the quality of the available data. For example the activity measure *heated floor area* does not capture the development of indoor temperatures. However, there are no continuous time series of temperature measurements from the Swedish building stock and thus these effects are lumped with technical efficiency in the factor *delivered energy use per floor area*.

between 1994 and 2000 also means fewer observations: on average 36 observations per year for one- and two-dwelling buildings and 40 observations per year for multi-dwelling buildings. As some retrofitting and improvements have been made in buildings from the seventies and eighties, these data were adjusted upwards based on the annual improvements of these segments in the EN16 energy statistics series.

The energy surveys (EN16) do not include energy for non-heating purposes. However, the Swedish Energy Agency, makes annual estimates of the electricity use in the residential and service sector, divided into electric heating, electricity for household purposes and electricity for common purposes (Swedish Energy Agency, 2002). The figures for electricity for common purposes include electricity use in both non-residential buildings and for other services such as street lighting. The latter is subtracted based on comparisons with the estimates in Carlsson (1992).

All energy use for heating is adjusted for annual changes in the climate, using degree-day[2] statistics from the Swedish Meteorological and Hydrological Institute (SMHI). We apply Statistics Sweden's method, correcting for half of the relative deviation from the normal year which is defined as the average in the period 1961–1979. This means that if a year has 10 per cent more degree-days than the normal year (i.e. a cold year), then the measured energy use is divided by 1.05. For the coldest year in the time series (1985) the measured energy use for heating is corrected by minus 7 per cent and in the warmest year (2000) by plus 12 per cent. This is a conservative correction method compared to that often used in international comparisons where the measured energy use is divided by the total number of degree-days. Appendix A gives a justification for the use of this method.

2.2.4. Primary energy

Primary energy is calculated from the statistics of delivered energy by adding losses upstream in the energy supply system. In this analysis, we include conversion and distribution losses in the electricity and district heating systems. Losses in refining, storing and transportation of oil and wood fuels are not included. Primary energy use itself is not a very good measure of energy efficiency in buildings but it serves as a complement to trends in delivered energy use as it includes effects of structural changes in the energy system which are hidden in the statistics of delivered energy.

For electricity production, the following efficiencies are used: 0.85 for hydro power (as used by Statistics Sweden), 0.33 for nuclear power, 0.88 for combined heat and power, 0.4 for coal condensing power (in Denmark), and 0.35 for oil condensing power. A different approach is the OECD's "fossil fuel equivalent method" in which all electricity is treated as had it been produced in traditional thermal power plants with constant efficiency of 0.385. In Sweden, this would result in a much higher primary energy use due to a large share of hydropower. Contrary, the traditional Swedish method which accounted for primary energy use in nuclear power plants as the output of electric power (an efficiency of 1) would show a considerably lower primary energy use.

Time series of losses in electric power distribution and in conversion and distribution of district heating are taken from Swedish Energy Agency (2002).

2.2.5. Heating efficiencies of energy carriers

Different energy carriers have inherent differences in the efficiency for heating of buildings. In order to isolate the effect of changes between energy carriers, we apply estimates of heating efficiencies of different energy carriers in relation to electric and district heating.[3] Thus these relative ratios are fixed throughout the time series and do not include, e.g. improved furnace efficiencies. Estimates of these ratios vary surprisingly widely. We use the ratios 0.8 for oil to electric heating in one- and two-dwelling buildings and 0.82 for oil to district heating in multi-dwelling buildings as found in an internal analysis by NUTEK.[4]

Making direct comparisons of year-classes of buildings with different heating systems give ratios of 0.65 (increasing from 0.62 in 1978 to 0.67 in 2000) for oil to electric heating in one- and two-dwelling buildings, and around 0.77 for oil to district heating in multi-dwelling buildings. However, particularly older buildings with electric heating were often built with extra isolation as electricity was still more expensive than oil and chosen mainly for convenience (Elmroth, 2002). Also in the 1980s, the building standard included special requirements for buildings with direct electric heating (the ELAK-standard). Thus oil-heating systems may not be quite as inefficient as indicated by such comparisons.

Other estimates come from the IEA (e.g. OECD/IEA, 1997)[5] which uses 0.66 for oil and 0.55 for solid fuels in

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[2] The number of degree-days is defined by the SMHI as the difference between +17°C and the daily average temperature summed overall days in January, February, March, November and December, days with <+12°C in April and September, days with <+10°C in May, June and July, days with <+11°C in August and days with <+13°C in October.

[3] Electric heating and district heating also result in heating losses as poor control systems lead to too high temperatures in certain spaces which cause unnecessary losses through airing. Similar problems arise when the load of free heat from, e.g. sunlight changes quickly.

[4] These figures are found in NUTEK (1995).

[5] The IEA and others use the concept *useful energy* which is derived simply by multiplying delivered energy by these fixed relations of heating efficiencies. It is a rather artificial measure, which is why we prefer to make a separate calculation of the influence from changing energy carriers.

Table 1
Carbon emission factors for fuel combustion applied in this study

	Emission factor		Source
	tC/TJ	kton CO_2/TWh	
Coal[a]	25.8	340	IPCC (1996)
Fuel oil	21.1	278	IPCC (1996)
Natural gas	15.3	202	IPCC (1996)
Peat[b]	26.3	347	Based on Åstrand et al. (1997)
Solid waste[c]	7.58	100	Olofsson et al. (2003)
Wood fuels	0	0	

[a] Bituminous coal.

[b] This emission factor is for peat from a typical Swedish bog. The IPCC figure is 28.9 tC/TJ.

[c] Includes carbon emissions from materials made from fossil fuel feed-stocks only. This emission factor is based on the presumption that there is an alternative not to produce waste from fossil feed-stocks. If instead the alternative is dumping of waste, the emission factor could be regarded as zero since the waste would oxidise anyway although slower.

relation to district and electric heating in all types of buildings. To the other end, Carlsson (1992) assumes ratios of 0.84 for oil to electric heating in one- and two-dwelling buildings, and 0.92 for oil to district heating in multi-dwelling buildings.

The use of wood fuels in one- and two-dwelling buildings have highly varying heating efficiencies. Wood is used both as a supplementary fuel in fire places with very low efficiencies and in modern pellets boilers (around 10 per cent of the wood fuels used) with efficiencies approaching those of electric heating. We use Carlsson's (1992) assumption of 0.61 for wood to electric heating.

2.2.6. *Carbon dioxide intensities*

The applied emission factors for various fuels are given in Table 1. These figures are for combustion only. The total fuel-cycle emissions for fossil fuels are about 5 per cent higher for fuel oil and up to 20 per cent higher for natural gas and coal (Gustavsson et al., 1995).

For cogeneration systems, allocation of emissions has been made on the basis of energy content. This is done for simplicity. Taking into account the higher value of electricity, allocation of emissions could be made based on, e.g. exergy, price or stand alone efficiency. Schlamadinger et al. (1997) give a description of these allocation methods.

In Eq. (5), we make an approximation of the carbon intensity c of Swedish electricity use taking into account imports and exports to neighbouring countries Norway, Denmark and Finland.[6] Data on the electricity production of these four countries are taken from the IEA. Data on annual imports and exports of electricity come from the organisation for co-operation between Nordic transmission system operators (Nordel)

$$c = \frac{c_{Swe}(E_{Prod} - E_{Exp}) + \sum_k (c_k E_{Imp,k})}{E_{Prod} - E_{Exp} + \sum_k E_{Imp,k}} \tag{5}$$

where E_{Prod} is the total Swedish electricity production, E_{Exp} is the total exports, and $E_{Imp,k}$ the imports from Norway, Denmark and Finland. In recent years, there have also been minor imports from Germany and Poland. The carbon intensities of imports and exports are approximated to each country's annual mix of electricity production.

3. Results

Fig. 3 shows an additive decomposition of carbon dioxide emissions from heating using the method described in Section 2.1. The figure illustrates the relative importance of each factor for changing carbon dioxide emissions between 1970 and 2000. For time series of the relative change of each factor, see Section 3.1.

The population growth of 10 per cent in combination with movement of people resulted in a large increase in the number of residents in one- and two-dwelling

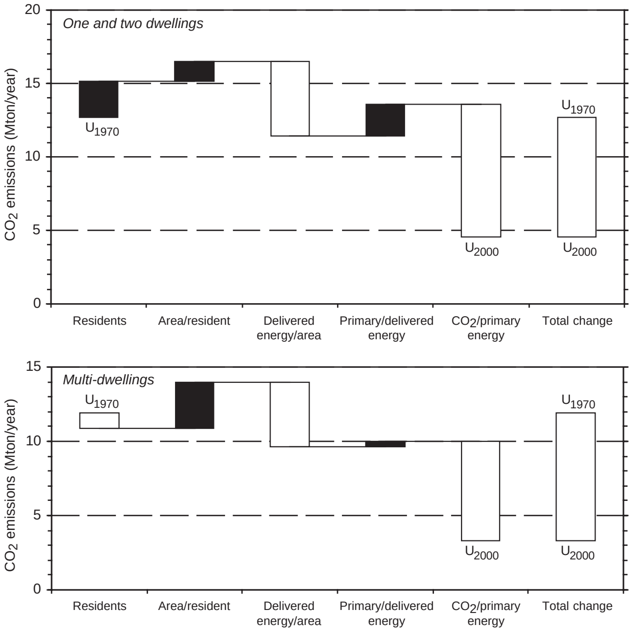

Fig. 3. Decomposition of CO_2 emissions U using the Parametric Divisia Method for 1970–2000. The columns describe the isolated contribution of each factor to changing CO_2 emissions, all other factors kept constant. Black columns represent increases and white columns represent decreases. The results are presented in an additive form, i.e., e.g. the sum of the first two columns describes the total contribution from changing floor areas. The diagram should be read from left to right starting with the emissions in 1970 (U_{1970}).

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[6] On the margin, it is often assumed that changes in Swedish electricity use are coupled to changes in imports of coal condensing power from Denmark. This is worth noting but is not applicable in this context.

buildings whereas the number of residents decreased slightly in multi-dwelling buildings. The increase in heated floor areas, represented by the two columns to the left, were more than compensated for by the decreasing factor *delivered energy/area*. The changes in this factor are analysed in detail in Section 3.2.

For one- and two-dwelling buildings, the factor *primary/delivered energy* increased, mainly due to the increased use of electricity for heating (Section 3.3). For both one- and two-dwelling buildings and multi-dwelling buildings, the factor *CO_2/primary energy*, i.e. substitution of fuel, was the most important factor behind the decreasing emissions (Section 3.4).

3.1. *Trends behind carbon emissions from heating*

In this section, we analyse time series from 1970 to 2000 of the five factors from Eq. (4) and Fig. 3. The time series are shown in indexed forms in Figs. 4 and 5 for one- and two-dwelling and multi-dwelling buildings, respectively. The absolute data are given in Appendix B.

In the stock of one- and two-dwelling buildings, delivered energy per floor area decreased rapidly between 1970 and 1974. The most dramatic change took place between 1973 and 1974 which correlates well with the first oil crisis. The changes between 1970 and 1973 are more difficult to explain, although around half can be attributed to the new construction. As shown by the increasing factors, *residents* and *floor area/resident* the rate of new construction was very high in this period and we will show in the following section that the energy use per floor area was only half as high in the new construction as in the old stock of buildings.

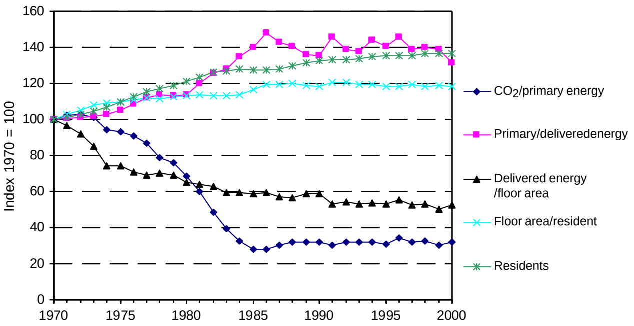

Fig. 4. Relative trends of carbon dioxide emissions from heating in multipliable factors for one- and two-dwelling buildings.

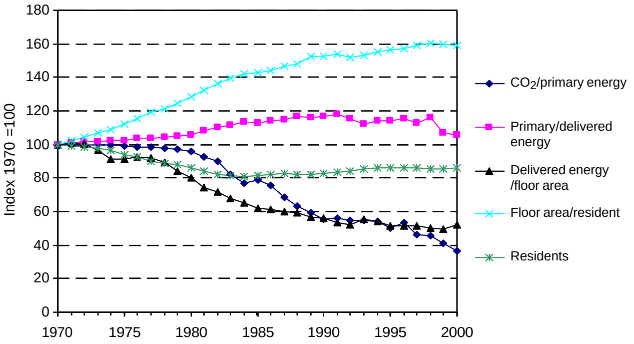

Fig. 5. Relative trends of carbon dioxide emissions from heating in multipliable factors for multi-dwelling buildings.

The dramatic reduction in delivered energy intensity during the first oil crisis is likely to have been mainly a result of changing user behaviour, which also could explain the slight increase in 1975. The delivered energy intensity fell more continuously between 1975 and 1983. After 1983, the decrease was only 10 per cent or on average 0.6 per cent per year. All five studied factors (Fig. 4) remained strikingly constant during the last 15 years of the period, which also resulted in constant carbon dioxide emissions.

About 400,000 one- and two-dwelling buildings were constructed in the seventies compared to only 55,000 buildings in the nineties. In total, the new-built heated floor areas from the period 1970–2000 constitutes about 40 per cent of the present stock.

For multi-dwelling buildings, the decline in energy intensity in the early seventies is not as striking as it is for one- and two-dwelling buildings. This can be explained by a lower influence of user behaviour, since residents in multi-dwelling buildings usually have fixed heating bills as a part of the rent to the facility owner. The decline is however more conspicuous between 1977 and 1992, after which it has stagnated. Carbon dioxide emissions continue to drop due to the continuing extension of the district heating systems, which is shown in Fig. 9. This is also the case for non-residential buildings.

The total heated floor area has increased more in one- and two-dwelling buildings than in multi-dwelling buildings, but migration towards one- and two-dwelling buildings has made the floor area per resident factor grow faster for multi-dwelling buildings.

3.2. *Changes in delivered energy intensity*

The changes in delivered energy intensity shown in Figs. 4 and 5 are the result of both technical changes and changes in user behaviour. However, the available data do not allow an analysis of the importance of changing indoor temperatures and it would be even more difficult to assess the importance of, e.g. the behaviour of opening windows for airing. Thus this section will focus on the technical changes.

As mentioned in the previous section, changes in user may have been very important in first years of the time series, especially during the first oil crisis. It is thus reasonable to study technical changes in the period of 1975–2000. That is, not to say that user behaviour has remained unchanged in this period, but it is likely to

Table 2
Delivered energy intensity and activity changes between 1975 and 2000

	Delivered energy intensity changes				Activity changes
	Total (%)	Isolated gain due to factor			Floor area (%)
		New construction (%)	Energy carriers (%)	Free heat (%)	
One- and two-dwelling buildings	−29	−12	−5	−2	+34
Multi-dwelling buildings	−43	−11	−13	−1	+29
Non-residential premises	−44	N/a	−11	−15	+37

New construction is the isolated gain with no retrofitting measures taken in the building stock of 1975, Energy carriers is the gain due to changes between inherently different energy carriers (mainly oil substitution) and Free heat is the gain due to increased useful heat from electricity use for non-heating purposes.

have been less influential on the development. 1975 is also the baseline year for the "Energy—for what and how much?" study by Steen et al. (1981) (see Fig. 1).

Table 2 gives a summary of the isolated influence of different factors on the energy intensity compared to the total change in energy intensity and activity. The factors cannot be summed up additively as there is some intersection of data. For example, changing energy carriers may be linked to the new construction. The difference between the gain of the three isolated factors and the total change in energy intensity is mainly due to retrofitting of buildings (potentially the most important factor of all) as well as to some extent to positive or negative changes in user behaviour. These factors are described in the following sub-sections.

3.2.1. *Gain in delivered energy intensity due to new construction or retrofitting?*

How much of the change in delivered energy intensity can be attributed to the share of better new constructed buildings and how much is incremental improvements in the stock of old buildings?[7]

Fig. 6 shows specific energy use for both the total stock and new one- and two-dwelling buildings. This gives us the opportunity to estimate the influence of new construction and retrofitting measures in the process of improving overall efficiency. If we conserve the stock of 1975 at its efficiency of the time, we can calculate the hypothetical specific energy use in the year 2000, given only the effects of new and more energy efficient buildings. The area of new construction for each year can be approximated by the change in heated floor area.[8] This gives a value for 2000 of 222 kWh/m^2/yr, which is 30 kWh/m^2/yr less than in 1975. About 41 per cent of the improvement could thus be attributed to the new construction and 59 per cent to improvements in the existing stock (the latter figure also includes improvements in buildings constructed after 1975).

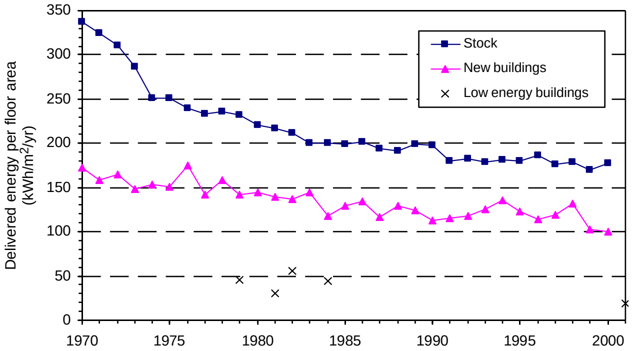

Fig. 6. The development of delivered energy use for heating per floor area of one- and two-dwelling buildings. The stock represents all heated floor area in a certain year. The curve for new buildings shows the energy use in the year of completion. Examples of low-energy buildings are included to illustrate the gap to BAT: Färgelanda 1979 (Eek, 1987), Uppsala 1981 (Wolgast, 1981), Malmö 1982 (Elmroth and Granberg, 1987), Tuggelite 1984 (Eek, 1987) and Lindås 2001 (Ruud et al., 2002).

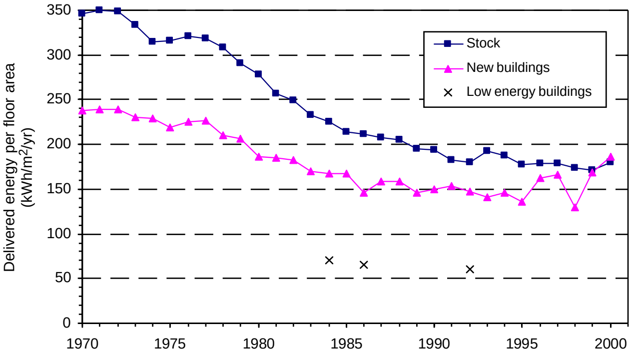

Fig. 7. The development of delivered energy use for heating per floor area of multi-dwelling buildings. The stock represents all heated floor area in a certain year. The curve for new buildings shows the energy use in the year of completion. Examples of low-energy buildings are included to illustrate the gap to BAT: Stockholm 1984 (Eriksson, 1993), Göteborg 1986 (Gustén, 1992) and Uppsala 1992 (Askensten, 1996).

Fig. 7 shows the corresponding development for multi-dwelling buildings. Here the total stock has

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[7] For example adjustment and improvement of heating systems, installation of heat exchangers and heat pumps, and additional insulation in windows, roofs and walls.

[8] For multi-dwelling buildings, the actual demolition was only slightly more than 3 per cent of the stock from 1975. There is no demolition statistics for one- and two-dwelling buildings, but the demolition rate is likely to have been even lower than for multi-dwelling buildings.

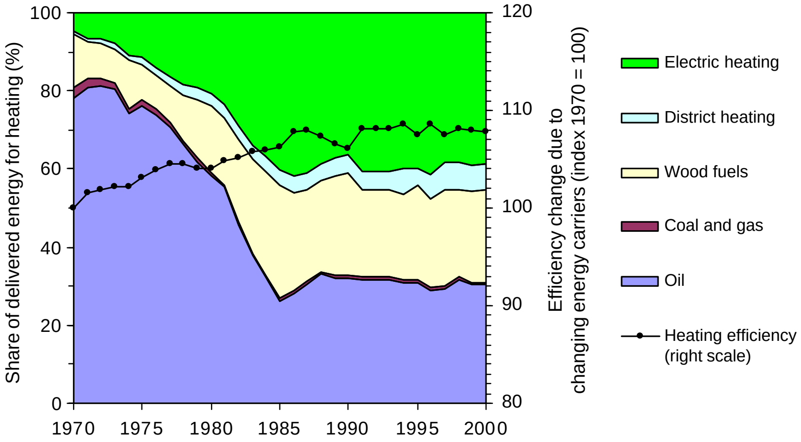

Fig. 8. Delivered energy mix for space- and water heating in one- and two-dwelling buildings and efficiency improvement (calculated as delivered energy) due to changing energy carriers.

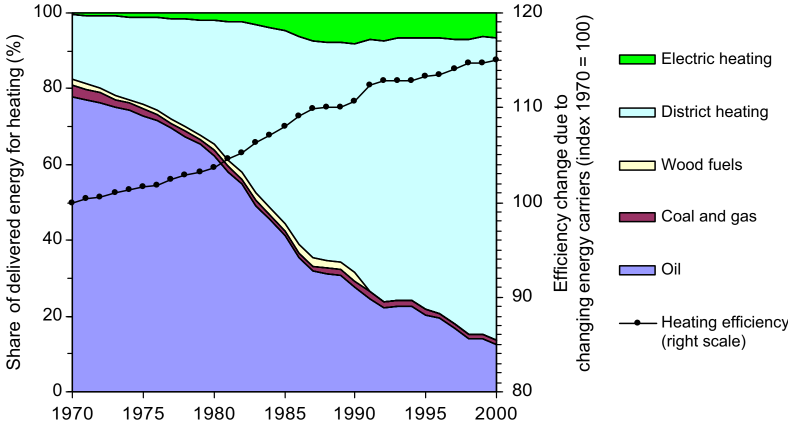

Fig. 9. Delivered energy mix for space- and water heating in multi-dwelling buildings and efficiency improvement (calculated as delivered energy) due to changing energy carriers.

improved much faster than the new buildings and even reached similar levels in recent years. The high energy use in new buildings in the last five years is somewhat uncertain due to fewer observations (see Section 2.2), but the fact that 4 of the last 5 years show higher energy intensities than buildings from the late eighties indicate an upward trend. This will be further discussed in Section 4. As for one- and two-dwelling buildings, we calculate the contribution of the new construction to the total decrease of specific energy use by conserving the stock of 1975 at its efficiency of the time and advancing the stock year by year from that point. This improvement attributed to the new construction is only 34 kWh/m^2/yr or 25 per cent of the total improvement.

3.2.2. Gain in delivered energy intensity due to change of energy carriers

As previously described in Section 2.2, delivered energy is a lumped measure, which changes due to different heating efficiencies (within buildings) for different energy carriers. Figs. 8 and 9 show the distribution of energy carriers between 1970 and 2000 for one- and two-dwelling buildings and multi-dwelling buildings, respectively. The transition from oil to electric heating in one- and two-dwelling buildings has increased the average heating efficiency within the buildings and in the meantime created even larger losses through conversion and distribution outside of the buildings, causing a net increase in primary energy use. However, focusing on the development of delivered energy intensity, this transition has generated an efficiency improvement of about 5 per cent between 1975 and 2000[9] (using the heating efficiency values from Section 2.2).

For multi-dwelling buildings, there have also been major changes between energy carriers contributing to the decreasing delivered energy. Losses in decentralised oil furnaces have been replaced by losses in the central

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[9] 6 per cent between 1970 and 2000.

district heating system. The energy mix of delivered energy for heating is given in Fig. 9. The total gain from changing energy carriers is 13 per cent between 1975 and 2000.

3.2.3. Gain in delivered energy intensity due to free heat from electrical appliances

Another potentially important factor is the increased "free heat" from electrical appliances. The availability of this energy is however limited, as thermostats fail to utilise peaks of quick fluctuations, and since electricity is also used outside of the heating season. Svensson and Kåberger (1991) estimate the year-based availability to 30 per cent, whereas Carlsson (1989) uses 70 per cent in his calculations. For a rough estimate of the importance of this factor we assume an average availability of 50 per cent of household electricity for heating.

For one- and two-dwelling buildings this contribution has increased from 15 kWh/m^2 in 1975 to 20 kWh/m^2 in 2000, which is 7 per cent of the total reduction of energy intensity for heating. For multi-dwelling buildings free heat from electrical appliances has only increased from 21 to 23 kWh/m^2 as the factor floor area/resident has increased much faster in multi-dwelling buildings. This gives a contribution of less than 2 per cent of the total improvement.

A major contribution from this factor can however be seen for non-residential buildings, where the use of electric power has increased substantially as seen in Fig. 10. The contribution from free heat in non-residential buildings has increased from 31 to 76 kWh/m^2 which corresponds to 28 per cent of the total reduction in energy intensity for heating. Heat from electrical appliances is also an increasing problem in non-residential buildings. The 151 kWh/m^2 of electricity use generates high temperatures also outside of the heating season, leading to an increasing demand for cooling. Some of this electricity is already used to run air-conditioning systems and in recent years there is also an increasing demand for district cooling services.

3.3. Changing patterns of end-use

Overall, the energy use in residential and service buildings has remained rather constant since 1970 in terms of total delivered energy. This development is the sum of a slightly decreasing energy use for space and water heating and an increasing use of electricity for non-heating purposes as shown in Fig. 10.

The increasing use of electricity for non-heating purposes in combination with an increased reliance on electric heating and district heating (Figs. 8 and 9) also increased the conversion and distribution losses outside of buildings. Most of this increase in primary energy use took place between 1974 and 1986, which correlates well with the implementation of the nuclear power programme (11 of the 12 reactors were started between January 1975 and September 1985).

3.4. Fuel substitutions

The total carbon dioxide emissions from energy use in residential and service buildings decreased from 39 Mton in 1970 to 12 Mton in 2000 of which heating constituted 35 and 11 Mtons, respectively. As shown in Fig. 3, the most important factor behind these changes was substitution of fuels. In short, there was a transition from oil to electricity and wood fuels for heating in one- and two-dwelling buildings (Fig. 8), and from oil to district heating in multi-dwelling buildings and non-residential buildings (Fig. 9).

In addition, major substitutions have been made in the fuel mix of electricity and district heating. In 1970, the energy supply to the district heating systems

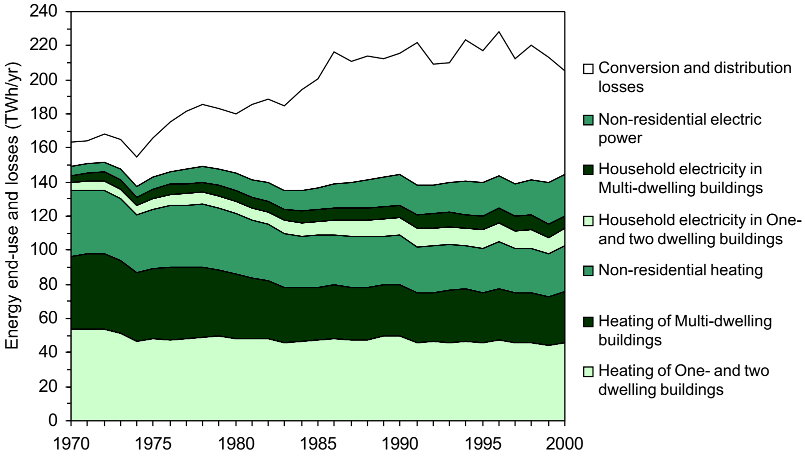

Fig. 10. Energy end-use and losses in residential and service buildings between 1970 and 2000. Energy use for heating is adjusted for changing number of degree-days (see Section 2.1).

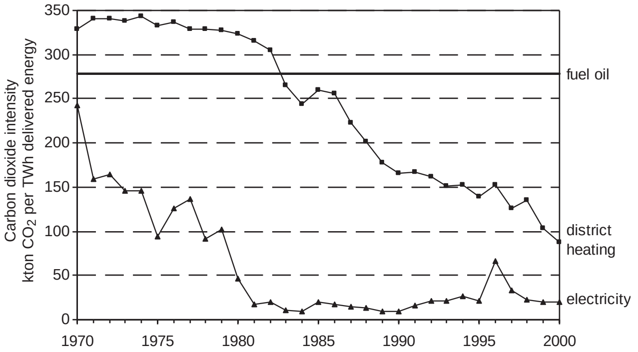

Fig. 11. The development of carbon dioxide emissions per delivered energy for electricity and district heating compared to fuel oil. Oil-heating systems generally cause larger losses within buildings than the two centralised options.

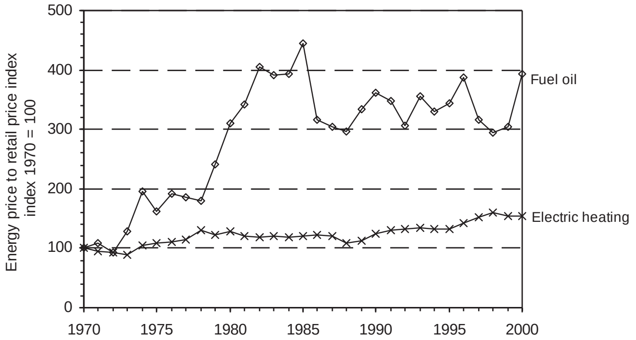

Fig. 12. Energy prices including taxes for fuel oil 1 and electric heating indexed in relation to retail price index which rose by a factor of 6.3 between 1970 and 2000 (Swedish Energy Agency, 2002).

constituted of 100 per cent oil and in 2000, the total share of fossil fuels was less than 20 per cent. For electricity production, oil stood for 20–30 per cent in the early seventies, but less than 5 per cent from 1981 and on. In the last 10 years, larger imports from Denmark where coal dominates electricity production has made the Swedish electricity use on average 35 per cent more carbon intensive than the domestic electricity production. Still, by international standards, nuclear and hydro power makes the carbon intensity of Swedish electricity use low.

The development of carbon dioxide intensity (emissions per delivered energy) of electricity and district heating is shown in comparison to the emission factor for oil in Fig. 11. Note that the measurement point—delivered energy—gives a higher carbon dioxide intensity for district heating than for oil in the seventies, due to conversion and distribution losses outside of the buildings.

4. Discussion

The technical potential for efficiency improvements in buildings was shown to be substantial in the late seventies (Steen et al., 1981). However, up till today this potential has only been realised to the point of balancing the growing activity in the sector. Even more striking is the fact that the delivered energy intensity (kWh/m^2/yr) has levelled off with no improvement during the nineties. Also, part of the improvement in delivered energy intensity during the seventies and early eighties was realised by moving losses from within buildings to conversion and distribution losses outside of buildings, which resulted in an increasing primary energy use.

The rate of new construction has been low during the last 10 years and this has kept the total energy use from increasing. However, the energy efficiency of the average new construction is not improving and in a longer perspective this is problematic given the long life cycles of buildings. The statistics for new-constructed multi-dwelling buildings indicate increasing energy intensities since 1995, with the same or lower energy efficiency than the average existing building (Fig. 7). The average new building actually uses more energy for heating than some buildings erected more than 100 years ago.[10]

Parallel to the slow development of the average new construction, the best available technology (BAT) on the market today is very efficient. For example, one- and two-dwelling buildings which rely solely on heat from appliances, people and passive solar energy for heating have already been demonstrated without extraordinary investment costs in Sweden (see Fig. 6 and Ruud et al., 2002).

Why did the development take this path?

4.1. The end to increasing oil prices

The oil price increased by 350 per cent in relation to consumer price index between 1970 and 1985 (Fig. 12). As the energy supply in the residential and service sector was highly dominated by oil in this period, this created a strong incentive for both energy efficiency measures and fuel substitution. This incentive decreased in 1985 when the oil price fell more than it increased in any year of the two oil crises. The falling oil price between 1985 and 1988 also coincides with a slightly increasing share of oil for heating in one- and two-dwelling buildings (Fig. 8).

4.2. The expansion of nuclear power capacity and low electricity prices

The nuclear power programme has been the centre of gravity for Swedish energy policy ever since the first oil

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[10] Buildings from around 1890 in central Gothenburg require about 150 kWh/m^2/yr of district heating (space and water heating) with no extensive retrofitting measures taken.

crisis in 1973 (see, e.g. Vedung, 2001). Parallel to the expansion of nuclear power capacity, programmes to foster energy conservation were launched. These programmes were partly successful, but also strongly hampered by the low electricity prices caused by the increase in capacity for electricity production. Fig. 12 shows that the electricity price remained fairly constant in relation to consumer price index during the seventies and early eighties while the oil price increased rapidly. The result was a substitution away from oil, which also at an early stage drastically reduced carbon emissions (before major political concerns about climate change).

The electricity use in the sector more than doubled between 1975 and 1990, corresponding to six nuclear reactors[11] (one half of the total capacity of nuclear power). The electricity price in Sweden today is still low by international standards and the electricity use per capita is 2.5 times as high as the average of the European Union (Swedish Energy Agency, 2002).

One example of energy efficient technologies which was seen to have a major potential by Steen et al. (1981) was heat pumps for one- and two-dwelling buildings. However, low electricity prices made payback times longer and the implementation has been relatively limited. In 2000, only 2.3 per cent of the one- and two-dwelling buildings were heated by heat pumps taking energy from bedrock, soil or water (Statistics Sweden, 2001).[12] However, it should be noted that the sales of heat pumps has increased rapidly in recent years.

4.3. *Strong building companies—weak contractors*

In the sector of multi-dwelling buildings, the distribution of responsibility is not always clear. There are several actors which directly or indirectly influence the energy use in buildings: mainly the construction companies, the contractor/property managers, the residents and the authorities. In 1995, the law regulating construction was rewritten to clarify the responsibility of the contractor in the construction process. The contractor should guarantee the technical quality of the construction and the authorities (the municipality) should only carry out inspections. Technical descriptions are no longer part of the application for building permits.

However, today the formally responsible contractor for multi-dwelling buildings is typically a small housing co-operative with little knowledge in building techniques, law and property management (SOU, 2002, p. 115). Thus in practice, the building company often controls the whole building process.

In the short term, an economically rational consequence of these circumstances is that the construction cost is minimised while the life cycle cost including the heating cost is not given the same weight. Thus weak contractors in relation to the building companies may be one reason behind the trend of increasing energy use in the new construction of multi-dwelling buildings.

4.4. *Weak rules and regulations*

Comparing the development of regulations in the building standard to the energy efficiency of average new-constructed buildings (Figs. 6 and 7), it is difficult to prove a strong correlation. The SBN 75 standard which came into force in 1977 meant a significant strengthening of the insulation requirements, but no major changes are seen in that year, although it may have been important for raising the lowest level of performance. Engebeck (1984) concluded that the coefficient of transmittance for walls did indeed decrease by 14 per cent 1977, but that this was much less than expected as the energy use in buildings from the early seventies had been overestimated.

The requirements for heat exchanging in larger buildings were strengthened in 1980, which correlate with a decrease in delivered energy intensity in new multi-dwelling buildings (but also with increasing energy prices). However, in the BBR 94 (1995) these requirements were lifted for buildings heated with less than 50 per cent fossil fuels. This exception includes district heating, which is the most common energy carrier in multi-dwelling buildings, and may thus be one reason behind the high values in the late nineties.

The building standard may also have had long-term educational effects, which are not revealed by year-to-year changes. Anyhow, the total influence on energy efficiency seems small, which may simply be due to that the regulations have been too easy to meet without major improvements.

Another possible problem concerns the manner in which the standard fulfilment is demonstrated. Elmroth (2002) found that the measured energy use in a number of multi-dwelling buildings in Stockholm was between 50 and 100 per cent higher than the calculated energy use. The computer program used for these calculations is simple in relation to the complex physics of buildings. It is also common that components and materials are changed for economical reasons later in the building process, without making new energy calculations.

In addition, the number of inspections has decreased since the rewriting of the law in 1995. Some municipalities do not make inspections at all (Boverket, 2001). This may be especially problematic given the

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[11] The technical potential for reducing energy use within the residential and service sector according to the BAT scenario in Steen et al. (1981) corresponded to 16 nuclear reactors.

[12] Bedrock/soil/lake heat pumps make up a separate category in the energy statistics. Combinations of electric heating and smaller heat pumps taking energy from air are not included in this figure.

imbalanced relation between contractors and building companies.

4.5. *Weak incentives for changing user behaviour*

Measurements of indoor temperatures between 1982 and 1992 showed that, on average, apartments in multi-dwelling buildings had 1–1.5°C higher temperatures than one- and two-dwelling buildings. Residents in multi-dwelling buildings have small incentives to save on heat expenditures, since the individual energy use for heating is not measured and the bill is a fixed part of the rent. The potential for energy savings through individual measurements and debiting is in the range of 5–10 per cent for space heating and 15–30 per cent for water heating (Berntsson, 1999). Individual measurements of space and water heating have been advocated for decades but the implementation in Sweden today is still very limited.

4.6. *Design*

There is an apparent trend towards increasing glass surfaces, especially in non-residential and multi-dwelling buildings, as well as increasing ratios of wall to floor area. These design features have a negative influence on the energy balance of new buildings.

5. Conclusions and recommendations for policy makers

It is apparent that the improvement in energy efficiency of existing buildings is strongly price driven. As discussed in the preceding chapter, the energy efficiency of residential buildings improved substantially when oil prices increased between 1972 and 1985 and as the oil price stabilised so did the level of energy efficiency. However, the effect of increasing oil prices on energy efficiency was also limited by the support to investments in power production which favoured substitution rather than efficiency. This was especially pronounced in one- and two-dwelling buildings, but electricity also gained a substantial share of the energy supply to district heating during the eighties.

There may be a number of reasons why energy efficiency often falls short in relation to supply strategies. The problem of imperfect information is typically more pronounced in the market of energy efficiency where the service may consist of a series of small changes with unclear estimates of costs and benefits. Unlike energy supply issues which are driven by major actors, energy efficiency also lacks influential advocates. In addition, investments in energy efficiency which are often made by households or landlords generally require much shorter payback times than investments in supply extension made by major specialised energy companies.[13]

Promotion of energy efficiency in the new construction seems to be particularly complicated since the distribution of costs and benefits between actors is ineffective. In a shorter perspective, there are no obvious incentives for the building companies to invest in energy efficiency and the formally responsible contractors of new multi-dwelling buildings often do not possess the appropriate knowledge of energy issues. Moreover, to the residents energy cost is a small and well-hidden part of the total rent and energy efficiency is merely one of many qualities valued in a building. Some of these, such as large glass surfaces, may even counteract energy efficiency.

Based on these conclusions we recommend the following:

5.1. *Not to support supply substitution at the expense of energy efficiency*

An implementation of the parliament decision to phase out nuclear power will lead to the greatest transition of the Swedish energy system since the nuclear power expansion in the seventies and eighties. It is therefore important to learn a lesson from the previous transition. The most prominent measure for reduced oil dependence after the oil crises was an increased supply of electricity and as a result the potential of improved energy efficiency was poorly utilised. In the coming transition, it will be important to better balance the attention between supply substitution and energy efficiency.

There were also long-lasting structural effects induced by the nuclear power expansion which should be borne in mind when planning the expansion of other large technical systems. For example, extensions of district heating system require a certain level of "energy density" to be profitable. Large investments in heat distribution systems may thus introduce an incentive to hamper improvements in energy efficiency. Especially when new residential areas are built, district heating and high energy efficiency (giving a low density of energy demand) make no good combination. This could lead to a path dependency, where the choice between supply and demand strategies may cause a permanent lock-in. The already mentioned exception to the rule of heat exchanging for buildings with district heating is one example were policies favour substitution at the expense of energy efficiency.

It should also be remembered that the price sensitivity differs between fuel substitutions and energy efficiency improvements. The quick changes of the fuel mix in

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[13] This is sometimes referred to as the payback gap and is discusses by, e.g. Verbruggen (2003).

district heat production in the eighties and nineties show that fuel substitutions are relatively easy to make if price incentives exist. These incentives could be reversed if, e.g. the prices of bio-fuels increase. Efficiency improvements on the other hand have been found to be almost irreversible as the elasticity to falling energy prices in the residential sector is close to zero (Haas and Schipper, 1998). To increase energy efficiency is thus a stable and long-term strategy to reduce emissions.

5.2. Regulations to affect user behaviour

The previously mentioned energy saving through individual measurements and debiting of heat is a potential waiting to be utilised. In, e.g. Denmark and Germany, individual measurements are already standard and there is no good reason why it should not be compulsory in the new construction. A common argument against individual measurements is that it is impossible to achieve a fair division of costs between households, since e.g. there is conduction of heat between apartments and the heat losses are larger in the top floor than further down in a building. However, compared to the current system of flat monthly bills, the system of individual measurements seems to both lower energy use and increase fairness.

5.3. Regulations to improve technical performance

A well-functioning energy standard for buildings could be a useful tool for the long-term transition towards a more energy efficient building stock. However, currently the standard has little effect. We have shown that the new construction of multi-dwelling buildings is worse than ever in relation to the stock of old buildings. Also, buildings complying with the current energy standard use far more heat than the best buildings on the market and the requirements have only been marginally tightened since the implementation of SBN 75 in 1977.

The main goal of the energy standard for buildings must be to ensure a low maximum level of energy use per floor area. The current standard is not based on the total function of the buildings (kWh/m^2/yr) but on the technical performance of components (e.g. W/m^{2}K for windows, etc.). The system is flexible to the point of allowing redistribution of efforts (e.g. windows are allowed to be worse if the roof is better than the standard level) but the end result is not guaranteed in terms of energy use and no follow-up is made.

A barrier for a function-oriented standard is that it would require a strong system for verification which makes it possible to isolate the influence and behaviour of facility owners and residents. Such verifications would of course demand lots of measurements, but simply the possibility to make follow-ups of the energy use would be a major driving force towards a better new construction. The contractor would be able to hold the builder responsible for a poor energy performance in the same way as for moisture damages.

To generate faster changes, it would also be reasonable to introduce energy standards for buildings which are retrofitted (today there is only a vague advice to follow the regulation of the new construction). Standards for retrofitting are also included in the new Energy performance of buildings directive (2002/91/EC) from the European Union.

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Appendix A. Climate correction method

In this study, we apply climate corrections to the energy use data according to the method of Statistics Sweden (Eq. (A.1))

$$E_{corrected}(t) = E_{measured}(t) \times \frac{1}{1 + \beta\,((D(t) - D_{normal\ year})/D_{normal\ year})} \tag{A.1}$$

Eq. (A.1) gives the corrected energy use for space and water heating $E_{corrected}$ in the year t as a function of measured energy use $E_{measured}$ and the number of degree-days D. $D_{normalyear}$ is the number of degree-days in a defined normal year (3855). β is a constant between 0 and 1 which describes the weight given to the climate correction. A β of 0 gives no correction whereas a β of 1

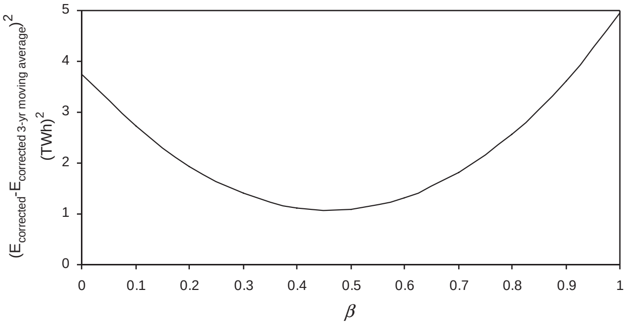

Fig. 13. The average square of $E_{corrected}$ minus the 3-year moving average of $E_{corrected}$ plotted for β between 0 and 1 during the period 1971–1999.

gives a correction directly proportional to the relative number of degree-days. Statistics Sweden assumes a β of 0.5 and the major reason for this low value is that energy use for water heating does not correlate to the number of degree-days. This assumption is tested below.

For β running from 0 to 1, we calculate the square of $E_{corrected}$ minus the 3-year moving average of $E_{corrected}$ (the average for the years $t-1$, t and $t+1$). In this way, we can find a value of β which minimises year-to-year changes without affecting the long-term trend. Fig. 13 shows the average result from this calculation for the years 1971–1999.

The least square is found for a β of 0.46. This supports the method to correct for half of the relative deviation from a normal year. Moreover, the optimal β shows no trend over time.

Appendix B. Data

The development of CO_2 emissions and energy use in the stock of one- and two-dwelling buildings is presented in absolute numbers in Table 3, with trends indexed to 1970 in Fig. 14. The corresponding development in the stock of multi-dwelling buildings is shown in Table 4 and Fig. 15. The development in non-residential buildings resembles that of multi-dwelling buildings with the exception of a faster growth in electricity use as seen in Fig. 5.

Table 3
Structure, energy use and CO_2 emissions for the stock of one- and two-dwelling buildings

		1970	1975	1980	1985	1990	1995	2000
Residents	Millions	3.84	4.21	4.66	4.90	5.09	5.19	5.24
Floor area	Mm^2	159	192	219	237	249	255	257
Energy use—heat[a]	TWh/yr	53.7	48.3	48.1	47.1	49.4	45.8	45.7
Electricity use—excl. heat[a]	TWh/yr	4.7	5.9	7.3	8.3	10.3	11.1	10.0
Total energy use[a]	TWh/yr	58.4	54.2	55.4	55.4	59.7	56.9	55.7
Total primary energy use	TWh/yr	63.1	62.2	69.3	85.2	90.0	89.8	80.8
Total CO_2 emissions	Mton/yr	13.8	11.7	9.2	4.5	5.1	4.9	4.7

[a] Delivered energy.

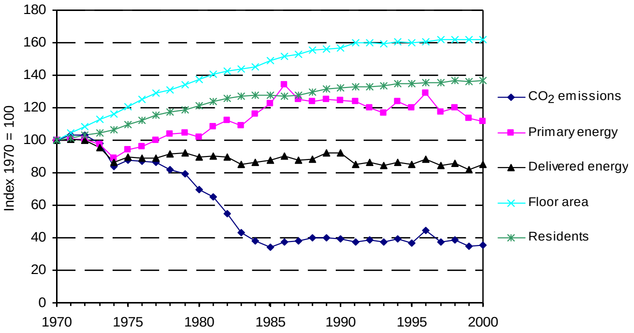

Fig. 14. The development over time of energy use and carbon dioxide emissions from space and water heating in one- and two-dwelling buildings.

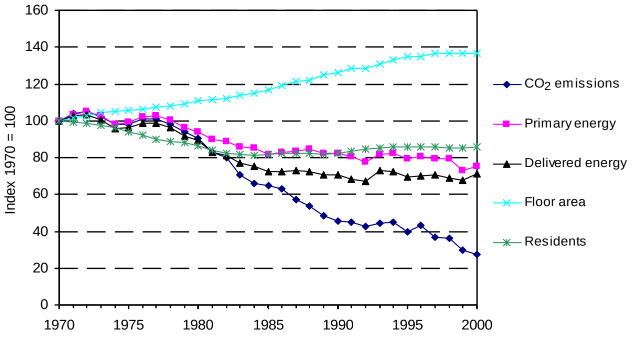

Fig. 15. The development over time of energy use and carbon dioxide emissions from space and water heating in multi-dwelling buildings.

Table 4
Structure, energy use and CO_2 emissions for the stock of multi-dwelling buildings

		1970	1975	1980	1985	1990	1995	2000
Residents	Millions	4.24	4.00	3.66	3.46	3.50	3.65	3.64
Floor area	Mm^2	123	130	136	144	155	166	168
Energy use—heat[a]	TWh/yr	42.5	41.1	37.9	30.8	30.0	29.5	30.3
Electricity use—excl. heat[a]	TWh/yr	4.5	5.6	6.3	6.7	7.6	8.6	7.7
Total energy use[a]	TWh/yr	47.0	46.7	44.3	37.5	37.6	38.1	38.1
Total primary energy use	TWh/yr	51.5	53.1	52.8	49.9	52.0	53.1	47.8
Total CO_2 emissions	Mton/yr	13.0	12.2	11.0	7.8	5.5	4.9	3.4

[a] Delivered energy.

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