Architecture and Energy:

Regulative and architectural paradigms for low-energy housing in Denmark

Rob Marsh, Senior Researcher, Architect MAA, PhD (Corresponding author)
Danish Building Research Institute, Aalborg University
Dr. Neergaards Vej 15, DK-2970 Hoersholm, Denmark
T: +45 21 65 08 87
E: rom@sbi.dk

Vibeke Grupe Larsen, Consultant, Architect MAA
Vglcph aps.
Vesterbrogade 24B-2, DK-1620 Copenhagen V, Denmark
T: +45 26 28 02 89
E: vgl@vglcph.dk

Michael Lauring, Assistant Professor, Architect MAA, PhD
Instutute for Architecture and Design, Aalborg University
Gammel Torv 6, DK-9000 Aalborg, Denmark
T: +45 99 40 99 44
E: mlau@aod.aau.dk

Date of Submission

XX.03.2009

Abstract

The interplay between regulative frameworks and traditional low-energy architectural paradigms in Denmark is examined, showing that low space heating demand does not equate to low primary energy consumption.

Total number of words

Approx. 4,850 words (excluding references).

Introduction

Architecture can play an important role in reducing building energy consumption. However, society's energy-related concerns change over time, and that means the framework within which building energy consumption is regulated also develops over time. This has an effect on how low-energy paradigms are defined, and that in turn creates new challenges for the architectural profession. This article therefore investigates the interplay between regulative frameworks and design paradigms for low-energy architecture in Denmark, with focus on housing:

- The first part provides an overview by looking at the changes in the housing stock's energy consumption since the first oil crisis in the 1970's, and by discussing the driving forces behind this transformation.
- The second part examines the changes in the regulative framework used to limit new housing's energy consumption since the 1970's, together with the effect that these regulations have had on new housing's total primary energy consumption.
- The third part describes the development of the traditional low-energy architectural paradigm in Denmark as a response to the changing regulative framework. This architectural paradigm is examined in relation to different regulative approaches focussing on reducing space heating demand and primary energy consumption in housing.
- The paper concludes by discussing how broader low-energy approaches, which integrate more energy related components in the design process, can be used to improve architectural and spatial quality, whilst also giving large reductions in buildings' total primary energy consumption.

This article is based on experiences from architectural research and practice regarding implementation of the European Union Energy Performance of Buildings Directive (EPBD) in Denmark. This was implemented in 2006 by introducing a radically different methodology for calculating building energy performance in the Danish Building Regulations. This energy performance calculation must be carried out using the Be06 software, developed by the Danish Building Research Institute. The Be06 software is widely used in the design process, for example in architectural competitions, and provides a common platform for energy analysis in the construction sector.

Historical Overview: Housing Stock Energy Consumption

There is considerable statistical material in Denmark relating to the housing and energy sectors stretching back to the 1970's. This means that it is possible to carry out a detailed analysis of energy consumption through time [Fig. 1].

In the years 1975 to 2005 the total population in Denmark has only grown by 7 %. However, because of the general economic growth during this period, the total floor area of the housing stock has grown 53 %. This has resulted in a growth in the average housing area per person from 34 m^2 to 48 m^2 per person, an increase of 43 % (Danmarks Statistik, 1975–2007).

Despite this large growth in the housing stock's total floor area there has been a 19 % reduction in the total energy consumption to meet the space heating requirements of the housing stock In contrast the total electricity consumption of the housing stock (excluding that to space heating, which is of negligible size) has risen 69 % over the same period (Energistyrelsen, 2007). Despite the growing floor area, Denmark has actually experienced an absolute reduction in total energy consumption to space heating in the housing stock. This is attributable to three factors:

- Energy planning has undergone a radical change to a more efficient system with a focus on district heating produced by combined heat and power in urban areas and individual gas boilers in suburban areas.
- Much of the older housing stock has been insulated, and older windows replaced with new and improved glazing systems.
- Changes in the Building Regulations since 1977 mean that all new housing has been constructed to much higher thermal insulation standards. (see Table 1).

The changes introduced since the 1970's have had a significant effect in reducing the demand for space heating in housing, and probably many other building types. This reduction stands therefore in sharp contrast to the change in the housing stock's total electricity consumption, which has grown at an even faster rate than the growth in floor area.

Modern society can be characterized by continuing and fluid processes of social and economic change (Baumann, 2000). Most industrialised societies have since the 1980's experienced a transformation towards a knowledge or information based society, and in this process there has been a transformation in how buildings are perceived and used (Gann, 2000). Buildings now have to meet advanced technological and functional demands, best expressed by the fast growth in the use of IT and electronic appliances. It can therefore be argued that these appliances are integral to modern buildings' functionality, and that the resulting electricity consumption is an integral part of running the building, in the same way that heat energy is perceived.

Regulative Frameworks: New Build Housing's Energy Consumption

The tendency for falling heat consumption and growing electricity consumption visible since the 1970's in the total housing stock is also noticeable in relation to the total primary energy consumption of new housing built over the last 30 years. This can be illustrated by looking at a two storey terrace house with a gross floor area of 120 m^2, a housing typology which reflects developments within Danish housing design and architectural traditions over the last 30 years (Christiansen, 1998; Mortensen & Welling, 2004). The analysis uses historical data for housing's electricity consumption presented above and compares it with the heat consumption for new build housing designed to comply with the relevant Building Regulations from 1972, 1977, 1998 and 2006:

- The total heat consumption is calculated by the Be06 software, and covers space heating and domestic hot water. It includes typical efficiency losses in the heating system using district heating. A primary energy conversion factor of 1.0 is used.
- The total electricity consumption, from Energistyrelsen (2007), covers domestic appliances, lighting and building services. The electricity consumption to lighting and building services is calculated by the Be06 software. This is subtracted from the total electricity consumption to give the remaining electricity consumption to domestic appliances. A primary energy conversion factor of 2.5 is used.

Before 1977: Historical Background

In the period before 1977 there was a very limited regulation of building energy consumption in Denmark. The regulations reflected measures introduced after the Second World War to balance concerns for design and construction quality in relation to shortages of construction materials and energy supplies (Lauring & Marsh, 2003). The 1950's and 1960's in Denmark were characterised by a considerable economic growth, improving social and economic standards, and not least a huge expansion in both the public and private housing sectors. The last Building Regulations before the oil crisis were introduced in 1972, and the required levels of thermal insulation [Table 1] could often be achieved with little or no insulation.

For typical new build housing from 1972, it can be seen that space heating accounts for over 60 % of the total primary energy consumption [Fig. 2]. It can therefore be seen as reasonable that the following regulative changes only focussed on limiting the fabric heat loss.

1977 to 1984: Regulation of Fabric Heat Loss

As a consequence of the 1970's oil crisis a series of measures were introduced to limit the fabric heat loss from new buildings. These regulations for housing, which were introduced in 1977, set standards for thermal insulation and levels for total glazing areas [Table 1].

With the introduction of the 1977 energy regulations, the groundwork for the regulative framework that has dominated low-energy architecture in Denmark was created. Whilst improved insulation standards can clearly be seen as advantageous, the limit on glazing areas showed that the regulative framework prioritised heat savings above daylighting conditions in housing. The result of this regulative paradigm was a generation of new housing with small windows, low daylighting levels and poor spatial quality (Lind, 1999).

For typical new build housing from 1977, the effects of these regulations was considerable, with the primary energy to space heating being reduced by approximately 50 % [Fig. 2]. Space heating now accounts for about 40 % of the total primary energy consumption.

1985 to 2005: Regulation of Space Heat Demand

In 1985 a new Energy Target calculation method was introduced which allowed for the use of a wider range of design and technological solutions to reduce space heating demand, such as passive solar energy, thermal mass and mechanical ventilation heat recovery. At this time, a definition for low-energy buildings was also introduced in the energy regulations, and housing with a space heating demand that was 50 % or less than the legal minimum could be called ‘low-energy’ (Byggestyrelsen, 1985).

In 1998, new standards for thermal insulation and levels for total glazing areas were introduced [Table 1]. The larger allowable area of glazing was a response to the development of new, highly insulated glazing systems which reduced heat losses without limiting solar gains, thus allowing for a greater exploitation of passive solar energy.

For typical new build housing from 1998, the effects of these regulations were not so extensive. Whilst the primary energy to space heating was reduced by approximately 40 % in relation to 1977, the total primary energy consumption was reduced by under 10 % because of the growing electricity consumption and overheating [Fig. 2]. Space heating now accounts for only 30 % of the total primary energy consumption.

2006 and Onwards: Regulation of Primary Energy Consumption

The European Union Energy Performance of Buildings Directive (EPBD) sets the common framework for energy savings in the construction and housing sectors. In Denmark the implementation of the EPBD was achieved by introducing a new chapter on Energy Consumption in the Building Regulations in 2006 (Erhvervs- og Byggestyrelsen, 2008), and this fundamentally changed the methods used to analyse energy consumption in today’s buildings.

The new regulations are based on regulating several components of energy consumption, integrating renewable energy production and expressing the total as primary energy:

- The new regulations for housing encompass energy consumption to space heating, domestic hot water, mechanical cooling and building services.
- Problems with overheating during the summer months are also regulated. The equivalent electricity consumption to eliminate temperatures over 26 ^{O}C with standard cooling equipment must also be calculated.

- A building's own renewable energy production, from both solar thermal and solar photovoltaic, is also taken account of in the new regulations.

There is also a consumption of energy associated with the production and distribution of different energy types. Data from the Danish Energy Agency has therefore been used to calculate relevant primary energy factors for the new energy regulations, where electricity consumption is multiplied by a factor of 2.5, whilst district heating, gas and oil are multiplied by a factor of 1.0. This is a pragmatic approach, using average values that have a pedagogical effect, but which can be scientifically validated (Energistyrelsen, 2007). These primary energy factors are broadly related to the CO_2 emissions and energy costs related to the consumption of these different energy types.

The new Danish energy regulations require that a building's primary energy consumption meets or is below maximum energy consumption requirements. This calculation must be carried out with the Be06 software, developed by the Danish Building Research Institute. It is based on relevant European standards or draft European standards, and all calculations are carried out on a steady-state monthly basis (Aggerholm & Grau, 2005).

The new energy regulations also introduced two new low-energy classes. 'Low-energy Class 2' is achieved with a primary energy consumption of at least 25 % under the minimum, whilst 'Low-energy Class 1' is achieved with a consumption of at least 50 % less.

For typical new build housing from 2006, the effects of these regulations were again not so extensive. Whilst the primary energy to space heating was reduced by approximately 25 % in relation to 1998, the total primary energy consumption was only reduced by 4 % [Fig. 2]. Space heating now accounts for under 25 % of the total primary energy consumption.

1972 to 2006: Transformations in Energy Consumption

It is necessary to reflect over the changes in new build housing's heat and electricity consumption over the last 30 years [Fig. 2]. Whilst the total heat consumption per unit floor area has been reduced by more than 65 % in the years from 1972 to 2006, the total electricity consumption has risen 10 % per unit floor area, so that the total electricity consumption is now larger than the total heat consumption.

Similarly, whilst the primary energy to space heating shows a reduction of 53 % between 1977 and 2006, the total primary energy consumption has only fallen by 13 %. It is also interesting to note that whilst the demand for cooling because of overheating was non-existent in 1972, it has by 2006 become responsible for over 10 % of the total primary energy consumption.

New buildings have become better insulated, and they typically use larger areas of highly insulated glazing. At the same, time electricity consumption and the internal heat gains from appliances have become larger. This means that it is now the total electricity consumption, including the summer's cooling demand because of overheating, that dominates new housing's total primary energy consumption, whilst heating demand has become smaller. Based on known data it is reasonable to assume that the same trends are true for many other important building types such as offices, education, etc. (Marsh *et al.*, 2008).

Traditional Paradigms for Low-energy Architecture

The regulative framework, with a historical focus until 2006 on reducing space heating demand, has in many years looked towards housing with an even lower consumption. This is expressed in the ‘low-energy’ housing regulation from 1985, which was defined as a space heating demand of 50 % or less than the legal minimum. The Danish architectural profession has played an active role in this process, and it is possible to outline an architectural response to changing regulative and social frameworks (Bech-Danielsen, 1999). As a response to the regulative framework to minimize space heat demand, the development of a traditional low-energy architectural paradigm can be discerned:

Superinsulated building fabric and glazing

The changes introduced in the 1977 energy regulations set focus on reducing fabric heat loss. Up to this point, brickwork had been the dominating load bearing and façade material in Denmark, finding expression in Jørn Utzon’s Kingo and Fredensborg housing developments from the early 1960’s, where internal and external brickwork flowed together with large areas of full height glazing to break down the boundaries between inside and outside space [Fig. 3].

However, the large focus on reducing U-values meant that traditional cavity wall solutions became less viable because of the need for more insulation. The new regulations accelerated the development towards multi-layered facades, with each layer serving its specific purpose. As the external rainscreen in these constructions can have many forms, heavy- or lightweight, the possibilities for architectonic expression were widened, and the old modernist dogma that a building should express its construction became redundant. The result was a move towards highly insulated constructive solutions consisting of either loadbearing concrete inner leafs with external insulation and rainscreen, or loadbearing, insulated timber framing with rainscreen. A good architectural example for this period is Vandkunsten’s Tinggården housing project in Herfølge from 1984, where the choice of materials reflects pragmatic concerns to flexibility, change and maintenance [Fig. 4].

Mechanical ventilation with heat recovery

With the introduction in 1985 of the new calculation method to reduce space heating demand, the foundations were laid for a stronger low-energy architectural paradigm with the use of mechanical ventilation with heat recovery. Balanced mechanical ventilation with heat recovery can minimise the ventilation heat loss by 60 – 80 %.

To successfully integrate heat recovery systems in housing requires considerable design skills. Firstly, there is a need to optimise plan solutions to minimise duct lengths and ensure air intakes and extracts are positioned correctly to ensure satisfactory air movement. Secondly, there is a need to integrate considerable amounts of building services technology within the building fabric in contrast to the relatively simpler natural ventilation. This can be seen in the Agernskrænten housing development in Ballerup by Henning Larsen from 1996, where specially developed square ventilation ducts for the heat recovery system were integrated into the lightweight plasterboard partitioning [Fig. 5].

Passive solar energy

The use of larger allowable areas of glazing in the energy regulations from 1998 was a response to the development of new, highly insulated glazing systems which reduced heat losses without limiting solar gains, thus allowing for a greater exploitation of passive solar energy. The architects, whose modernist visions of large glass facades had been suppressed for almost two decades, quickly caught on to the opportunity. Besides strong modernist images and a legitimate wish for better daylighting in buildings, passive solar heat gained a strong reputation for being environmentally friendly, so the urge and arguments were many.

During the 1990's a series of low-energy housing demonstration projects were designed by some of Denmark's leading architectural practices with an extensive use of passive solar energy. In these projects, the housing terraces were orientated north-south and glazing areas were redistributed, with larger glazing areas orientated to the south and smaller areas to the north. Good examples of this include Lundgaard & Tranberg's Solar

Terraces in Vonsild from 1994 and the EcoHouse99 developments in Skejby (Vandkunsten) and Kolding (3xNielsen) from 2001 [Figs. 6 and 7].

Research has since shown that most of these passive solar housing schemes have not actually delivered energy savings (Dollerup, 2002). They have also had severe problems with overheating during the summer (Hans Bjerregærd Rådgivning ApS., 2001), and this has often resulted in severe comfort problems, with users for example renting electrically driven portable cooling units to maintain comfort (Kristiansen, 2000). Informal discussions that this article's authors have had with residents reveal that internal temperatures between 30 and 45 ^{O}C are experienced during the summer months in these housing schemes.

Traditional Low-energy Architecture and Space Heating Demand

The traditional low-energy architectural paradigm has responded to the regulative framework by aiming to minimise the space heating demand by the following parameters:

- Superinsulated building fabric and low-energy glazing.
- Mechanical ventilation with heat recovery.
- Passive solar energy with larger glazed areas to the south and reduced areas to the north.

The low-energy architectural paradigm that comes to expression through these parameters has dominated low-energy housing in Denmark for the last 15 years. It has resulted in much uncritical coverage from the architectural profession, where the architectural and energy related qualities of these projects have been highlighted, but without any serious analysis of whether they actually deliver any reductions in energy consumption (Beim *et al.*, 2002).

Whilst it is undeniable that this traditional paradigm for low-energy architecture can deliver substantial reductions in space heating demand, there is evidence that aspects of this approach have created other energy-related and indoor comfort problems. At the same time, the data previously presented shows that new housing now has a greatly reduced heat consumption, whilst electricity consumption has continued to rise over time. It is therefore relevant to examine this traditional low-energy architectural paradigm in relation to different regulative frameworks.

The older energy regulations, used between 1985 and 2005, were only focussed on reducing space heating demand. This regulative framework can be used to examine the typical two storey terrace house with a gross floor area of 120 m^2, and designed to comply with the current Building Regulations. A cumulative analysis is carried out with the above named parameters from the traditional low-energy architectural paradigm [Table 2].

The effect on the space heating demand is calculated with the Be06 software. The results show that the combination of the narrow regulative framework together with the architectural design paradigm focussing on reducing space heating demand has a considerable effect [Fig. 8]. The cumulative effect of all three parameters reduces the space heating demand by 65 % in relation to the typical housing:

- Superinsulation: 35 % saving.
- Mechanical ventilation with heat recovery: Extra 15 % saving.
- Passive solar: Extra 15 % saving.

It can therefore be seen that the traditional low-energy architectural paradigm can, without problems, reduce the space heating demand by over 50 %, the threshold for achieving the ‘low-energy’ status under the traditional regulative framework.

Traditional Low-energy Architecture and Primary Energy Consumption

The new energy regulations, introduced in 2006 as a consequence of the EBPD, have a broader approach, focussing on the primary energy consumption to space heating, domestic hot water, overheating/cooling and building services. This regulative framework can be used to again analyse the typical two storey terrace house with the same parameters from the traditional low-energy architectural paradigm.

The primary energy consumption is calculated with the Be06 software, and the results show a very different picture [Fig. 9]. The cumulative effects of superinsulation reduces the primary energy consumption by under 30 %. However, the utilization of mechanical ventilation with heat recovery and passive solar energy have absolutely no effect, and actually results in a slight increase in the primary energy consumption:

- When the primary energy consumption to building services is included, the use of mechanical ventilation with heat recovery shows no advantage. This is because the savings in space heat consumption are more than neutralised by the higher electricity consumption these systems are responsible for. There is little difference between mechanical ventilation with heat recovery and natural ventilation
- When the primary energy consumption to the cooling demand from overheating is included, the use of passive solar energy also shows no advantage. When the glazing distribution is changed so that a large proportion is facing to the south, the reduction in space heating is neutralised by the growing cooling demand from overheating.

These results show how differing frameworks for regulating low-energy buildings give markedly different results. Traditional low-energy architecture can be seen to give very large reductions in space heating demand. However, when this traditional low-energy approach is examined with a broader regulative framework, totally different results emerge, with the savings in space heating demand being more than neutralised by a larger electricity consumption and indoor comfort problems.

The use of passive solar energy, which historically has been promoted as an effective way to minimise space heat demand, can actually be very problematic in relation to the new Danish energy regulations, creating problems for indoor comfort and a growing cooling demand. For architects this changes the design focus from winter-related issues to summer-related problems.

The new energy regulations create a level playing field between natural ventilation and mechanical heat recovery systems. These results are also backed up by previous Danish research into heat savings contra extra electricity consumption for mechanical heat recovery systems (Aggerholm, 2001). Extensive literature surveys have also shown that mechanical systems do not give a better indoor climate than natural ventilation in Danish housing (Lauring & Marsh, 2003).

The historical focus in Denmark on regulative frameworks to reduce space heating demand have been very effective. However, this approach has had serious negative consequences, and the architectural paradigm developed for reducing space heating demand has been shown to result in indoor comfort problems and a high electricity consumption. It can be argued that the historical regulative framework set institutional barriers in relation to which energy saving strategies could be utilized by architects in the design process, but at the same time this regulative framework was unable to take account of the negative energy related consequences which the barriers themselves created.

It is therefore reasonable to assume that many of the so-called low-energy housing demonstration projects, designed by some of Denmark's leading architectural practices in the 1990's, and which utilized mechanical ventilation with heat recovery and passive solar energy, would have had a lower primary energy consumption if these strategies for reducing space heating demand had not been used.

New Paradigms for Low-energy Architecture

It has been shown how the regulative framework limits the focus for energy saving, and that this has been reflected in how the low-energy architectural paradigm has developed. Since the EPBD, with its broader low-energy definition, was only introduced in 2006, it is too early to discern a new low-energy paradigm in architectural practice. However, it can be argued that broader regulative frameworks, which encompass more components of building energy consumption, can result in changing architectural paradigms.

Built Form

Traditional low-energy paradigms have focussed on reducing space heating demand. This has resulted in a design focus on compact built forms that minimise the building's surface area in relation to the heated volume, and therefore reduce the fabric heat loss from the building. Compact built forms typically have very deep rooms, a central zone without daylighting and ceiling heights at the legal minimum. There is clear evidence that the use of these compact typologies has become more widespread for most building types in Denmark, including housing and offices (Mortensen & Welling, 2004; Thau, 2001), and is propelled by regulative, technological and economic concerns.

Deep buildings with limited ceiling heights will typically require a more extensive use of mechanical ventilation and artificial lighting since a large proportion of the floor area cannot use natural daylighting or ventilation. At the same time new buildings have become better insulated and the internal heat gains from electrical equipment, artificial lighting and building services have become larger, meaning that overheating and a growing cooling demand are more common. This means that the primary energy consumption to lighting, cooling and building services will often be larger than that to space heating. This indicates that spatial design can be a viable strategy in a broader low-energy paradigm.

Daylight quality and distribution is closely linked to a room's spatial proportion. Rooms with a greater ceiling height, highly placed windows and a limited depth can create better daylighting conditions with a more even daylight distribution (Leslie, 2003). This creates well lit rooms with better visual quality, and together with the use of low-energy lighting with daylight control, this strategy can greatly reduce the primary energy consumption to lighting. At the same time, buildings with greater ceiling heights, limited building depths and an absence of internal rooms are ideal for cross ventilation, and therefore strategies using controlled natural ventilation will be easier to implement. By combining natural daylight and natural ventilation, the internal heat gains from the building services can be greatly reduced, thereby reducing the cooling demand.

Glazing Area and Orientation

Traditional heat saving paradigms have promoted the use of large areas of south facing glazing to reduce space heating, and this has resulted in severe problems with overheating. It is therefore important to design buildings with a low energy consumption and a good thermal comfort in relation to summer conditions. Glazed areas need therefore to be designed so that their size and distribution is based on the need for daylight in each room, whilst their orientation is based on the need to minimise overheating and cooling demand. With the transformation from the industrial to the knowledge society, it is at the same time important that buildings are designed to allow for a growing use of VDU's, both at workplaces and in the home for work and leisure purposes.

For a given building there can be many advantages in orientating the rooms with the largest areas of glazing to the north so that the best daylighting conditions are created, including for VDU usage, whilst at the same time, the problems with overheating and cooling demand are eliminated (Marsh *et al.*, 2008). By consciously utilising daylight from the north, the remaining glazed areas can be distributed in relation to the need for daylight, and with the use of external shading devices so that sunlight can be utilised or excluded as required. Buildings with reduced areas of glazing to the south have also larger south facing façade areas where building integrated renewable energy can be placed.

Conclusions

This article has shown that the traditional low-energy architectural paradigm, whilst resulting in a large reductions in space heating demand, does not necessarily result in a low primary energy consumption, since heat savings can result in other energy-related and indoor comfort problems. The architectural profession needs therefore to be much more aware of the institutional barriers that regulative frameworks set in relation to which low-energy architectural paradigms can be utilized, and at the same time to be aware of the negative energy-related consequences that regulations themselves create.

In new Danish buildings, it is electricity consumption that dominates the total primary energy consumption. It is therefore argued that broader regulative frameworks, that encompasses more components of building energy consumption, will result in changing architectural paradigms. Here, a greater focus on the use of natural daylighting and natural ventilation can be used to improve the architectural and spatial quality in buildings, and give considerable reductions in total primary energy consumption.

This paper covers Danish conditions, but it is reasonable to assume that the same argumentation can be used in other countries that have similar climatic conditions, have a long tradition for effectively regulating heat consumption, and are well developed in the transformation to a knowledge based society.

Acknowledgements

The research presented in this paper has been supported by the Kuben Housing Foundation, The Danish Electricity Saving Trust and the Danish Energy Association's R&D Program for the Effective Use of Energy.

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Figure 1

Change in the Danish housing stock's total space heating consumption, total electricity consumption and total floor area, together with change in population from 1975 to 2005 (1975 = 100 %).

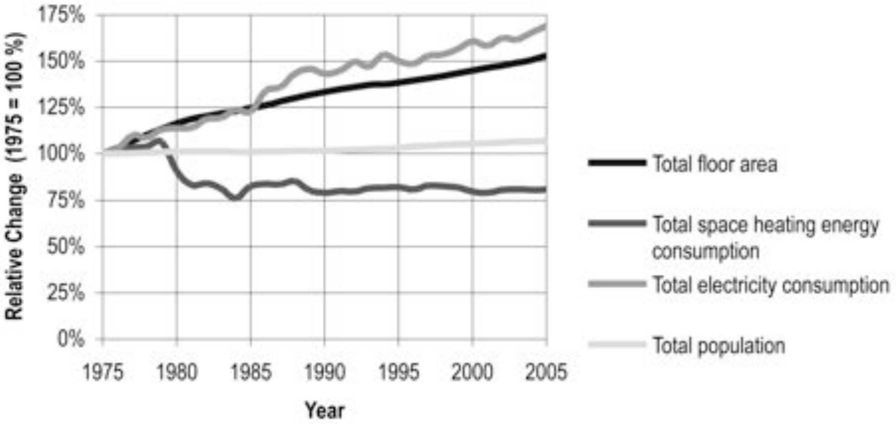

Figure 2

New build housing's total primary energy consumption per m^2 floor area for the years 1972, 1977, 1998 and 2006.

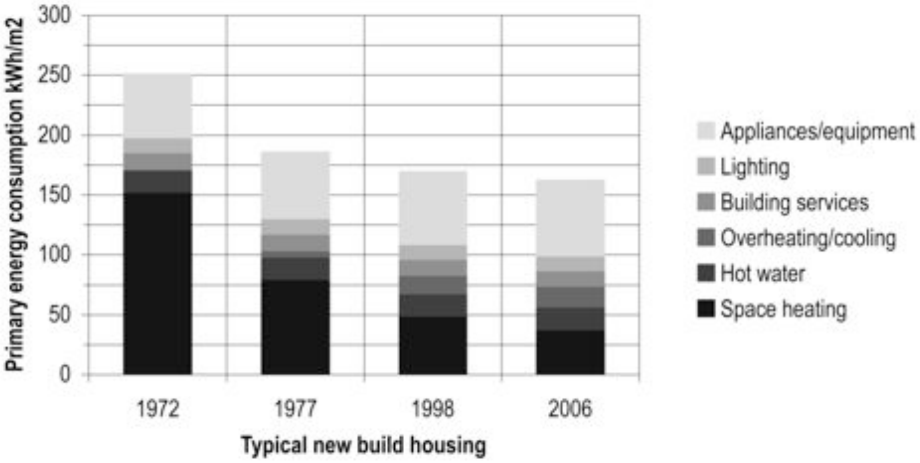

Figure 3

Architectural interplay between internal and external brickwork with large glazing areas. Kingo housing project, Helsingør; Jørn Utzon, 1960.

Figure 4

Pragmatic use of materials reflecting flexibility, change and maintenance. Tinggården housing project, Herfølge; Vandkunsten, 1984.

Figure 5

Plan and design solutions optimised for mechanical ventilation with heat recovery. Agernskræntenhousing project, Ballerup; Henning Larsen, 1996.

Figure 6

Extreme use of passive solar energy in suburban setting. Solar Terraces housing project, Vonsild; Lundgaard & Tranberg, 1994.

Figure 7

Extreme use of passive solar energy in urban setting. EcoHouse99 housing project, Kolding; 3xNeilsen, 2001.

Figure 8

Traditional low-energy architectural paradigm for new build housing calculated in relation to the regulative framework to minimize space heating demand per m^2 floor area.

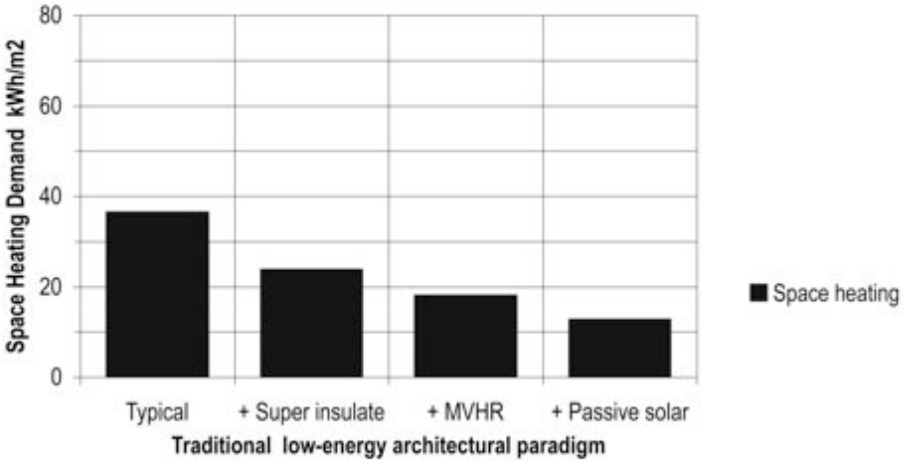

Figure 9

Traditional low-energy architectural paradigm for new build housing calculated in relation to the regulative framework to minimize primary energy consumption per m^2 floor area.

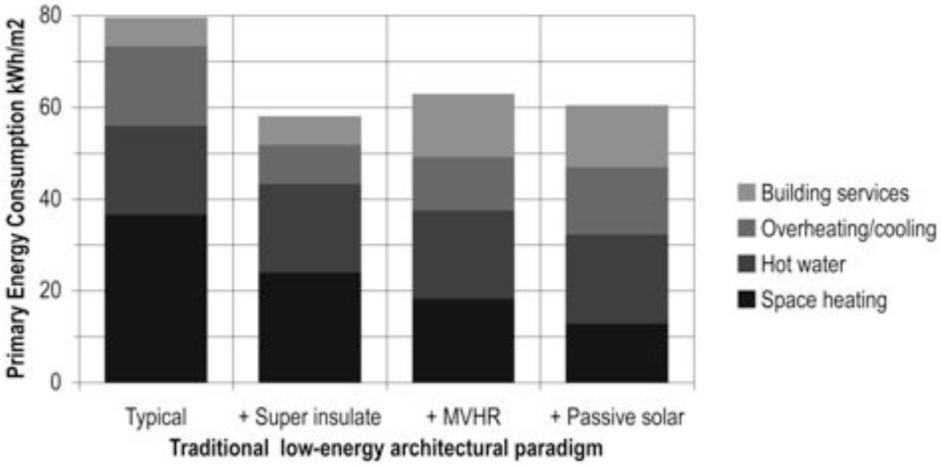

Table 1

Changes in maximum thermal insulation standards and maximum allowable area of glazing for housing in the Danish Building Regulations between 1972 and 2006.

Year	U-value W/m^2 K				Area of glazing
	Wall	Windows	Roof	Ground floor	As % of floor area
1972	1.00	3.60	0.45	0.75	No requirement
1977	0.40	2.90	0.20	0.30	15 %
1998	0.30	1.80	0.20	0.20	22 %
2006	0.20	1.50	1.50	0.15	22 %

References: Boligministeriet (1972); Boligministeriet (1977); Bolig- og Byministeriet (1998); Erhvervs- og Byggestyrelsen (2008).

Table 2

Parameters used to calculate space heating demand and primary energy consumption shown in Figures 8 and 9 .

Parameters	House Type	
	Typical	Superinsulate/MVHR/Passive Solar
U-value, external wall (W/m^2.K)	0.20	0.10
U-value, roof (W/m^2.K)	0.15	0.10
U-value, ground floor (W/m^2.K)	0.15	0.10
U-value, window (W/m^2.K)	1.50	1.00
	Typical/Superinsulate	MVHR/Passive Solar
Ventilation system	Natural ventilation	Mech. heat recovery
Ventilation rate (l/s.m^2)	0.30	0.30
Specific electricity consumption (J/m^3)	0	1,200
Heat recovery efficiency	N/A	65 %
	Typical/Superinsulate/MVHR	Passive Solar
Glazing area to south (% of façade)	40 %	70 %
Glazing area to north (% of façade)	40 %	10 %

Text to Figures

Figure 1

Change in the Danish housing stock’s total space heating consumption, total electricity consumption and total floor area, together with change in population from 1975 to 2005 (1975 = 100 %).

Figure 2

New build housing’s total primary energy consumption per m^2 floor area for the years 1972, 1977, 1998 and 2006.

Figure 3

Architectural interplay between internal and external brickwork with large glazing areas. Kingo housing project, Helsingør; Jørn Utzon, 1960.

Figure 4

Pragmatic use of materials reflecting flexibility, change and maintenance. Tinggården housing project, Herfølge; Vandkunsten, 1984.

Figure 5

Plan and design solutions optimised for mechanical ventilation with heat recovery. Agernskrænten housing project, Ballerup; Henning Larsen, 1996.

Figure 6

Extreme use of passive solar energy in suburban setting. Solar Terraces housing project, Vonsild; Lundgaard & Tranberg, 1994.

Figure 7

Extreme use of passive solar energy in urban setting. EcoHouse99 housing project, Kolding; 3xNeilsen, 2001.

Figure 8

Traditional low-energy architectural paradigm for new build housing calculated in relation to the regulative framework to minimize space heating demand per m^2 floor area.

Figure 9

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Text to Tables

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