NORDISK ARKITEKTURFORSKNING

NORDIC JOURNAL OF ARCHITECTURAL RESEARCH

1/2.2010

Architecture, Energy and Climate

NORDISK ARKITEKTURFORSKNING

Redaksjonens adresse
Nordisk Arkitekturforskning
Fakultet for arkitektur og billedkunst, NTNU
Eivind Kasa, Editor-in-Chief
Alfred Getz vei 3
7491 Trondheim
tel (+47) 73 59 50 07
www.arkitekturforskning.net

Tidsskriftets e-post:
nordark@ab.ntnu.no

Design og illustrasjon omslag
Alex Booker, NTNU

ISBN 978-82-92880-07-4

Trykk: Tapir Uttrykk AS, Trondheim 2010

Miljøfyrtårn®

Tidsskriftet er utgitt i samarbeid med
Nordisk Arkitekturakademi

NORDISK FORENING FOR ARKITEKTURFORSKNING

Styrets adresse
Nordisk Forening for Arkitekturforskning
President Peter Thule Kristensen
Kunstakademiets Arkitektskole
Philip de Langes Allé 10
1435 Kbh. K
tel (+45) 3268 6000
arkitektskolen@karch.dk

ABONNEMENT OG MEDLEMSAVGIFTER

PRISER 2008 Tidsskriftet er fritatt for moms Valuta	Sverige SEK	Danmark DKK	Finland Euro	Norge NOK	Utenfor Norden SEK
Abonnement enkeltpersoner*	350	290	38,5	320	425
Abonnement studerende/doktorand*	250	205	27,5	225	305
Abonnement 1 eks institusjon/bedrift*	525	430	57,7	475	625
Abonnement 3 eks institusjon/bedrift*	725	595	79,7	660	825
Kun medlemskap	50	45	5,9	50	50
Løsnummer	100	90	11,8	95	150
Løsnummer, dobbeltnummer	175	150	21,0	170	260
Årgang 87-00	100	90	11,8	95	150
Årgang 01-03	200	175	23,5	190	300
Årgang 04-06	225	200	26,9	215	280

*medlemskap for *én* person i Nordisk Forening for Arkitekturforskning.

Abonnement og løssalg
Nätverkstans ekonomitjänst
Box 311 20, 400 32 Göteborg
Tel. 031 743 99 05
Fax 031 743 99 06
E-post: ekonomitjanst@natverkstan.net
OBS! Subject: NA

Betaling i Sverige til ***Postgirot 419 03 25-3***
i Danmark til ***BG Bank 1-678-0995***
i Finland til ***Leonia Bank 80013-70633795***
i Norge til ***Den norske Bank 7877.08.13769***

Betaling i land **utenfor** Norden i
SEK med SWIFT-adresse
PGSI SESS Account no: 4190325-3,
Postgirot Bank Sweden
SE-105 06 Stockholm

Ikke send sjekker.
Ikke betal til svensk postgiro fra Danmark,
Finland og Norge.

NORDISK ARKITEKTURFORSKNING

NORDIC JOURNAL OF ARCHITECTURAL RESEARCH

1/2.2010

THE ARTICLES HAVE BEEN PEER REVIEWED BY AT LEAST TWO OF THE FOLLOWING RESEARCHERS:

ANNEMIE WYCKMANS, NTNU

ARNE FØRLAND, Aarhus School of Engineering

ELI STØA, NTNU

HANNE LEHRSKOV, Aarhus School of Engineering

HANNE TINE RING HANSEN,Rambøll, Denmark

INGER-LISE SAGLIE, University of Life Sciences, Ås

JAAN-HENRIK KAIN, Chalmers University of Technology

LARS-GÖRAN MATTSSON, Royal Institute of Technology, Stockholm

MATHILDE PETRI, Royal Danish Academy of Fine Arts, School of Architecture

PER HEISELBERG, Aalborg University

RASMUS LUND JENSEN, Aalborg University

THOMAS JUEL CLEMMENSEN, Aarhus School of Architecture

TOMAS SVENSSON, Swedish National Road and Transport Research Institute

TORBEN DAHL, Royal Danish Academy of Fine Arts, School of Architecture

MICHAEL JONES, NTNU

MARIE LOUISE ANKER, STFK

SIGMUND ASMERVIK, UMB, Ås

FINN HAKONSEN, NTNU

DAG KITTANG, NTNU

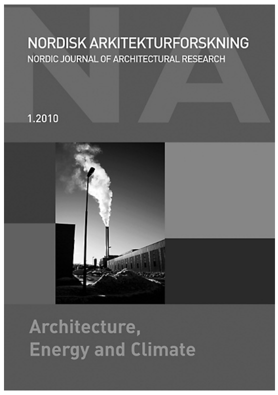
STAALE SINDING-LARSEN, NTNU

MAGNUS RÖNN, KTH

TIM ANSTEY, KTH

BIRGIT COLD, NTNU

ANNE KATHRINE FRANDSEN, SBI



Innhold: Vol. 22, No 1/2.2010

NORDISK ARKITEKTURFORSKNING – NORDIC JOURNAL OF ARCHITECTURAL RESEARCH

Towards a New Paradigm: Design Strategies for Architecture, Energy and Climate Change using Danish Office Buildings as a Case Study

Rob Marsh, Vibeke Grupe Larsen
and Jake Hacker

Nordic Journal of Architectural Research
Volume 22, No 1/2, 2010, 15 pages
Nordic Association for Architectural Research
Rob Marsh, Vibeke Grupe Larsen and Jake Hacker
Danish Building Research Institute, Aalborg University, Denmark

TOPIC: ARCHITECTURE, ENERGY AND CLIMATE

Abstract:

This paper argues that the understanding of architecture again needs to be widened if the architectural profession is to play an active role in combating climate change. The paper therefore examines past, present and future challenges for building energy consumption in Denmark as the basis for developing a new paradigm for zero-energy architecture.

There has been a radical transformation in building energy consumption over the last 30 years, with an absolute reduction in heat consumption and a rapid growth in electricity consumption, reflecting wider technological and social transformations in the movement from an industrial to a knowledge-based society. In new offices it is shown that electricity consumption now dominates the total primary energy consumption, whilst at the same time, climate change means that rising temperatures will result in falling heat demand and increasing cooling demand in the future.

With this background, a new paradigm for zero-energy architecture is developed that reflects the architectural design process. In this way, the architectural focus early in the design process on functional disposition, spatial quality and built form can act as the driving force in the movement towards zero-energy architecture that has good daylighting and indoor comfort, and is adapted to future climate change.

Keywords:
Zero-energy architecture, Integrated energy design, Climate change adaptation,
Office buildings, Knowledge-based society.

INTRODUCTION

The challenge of climate change is perhaps one of the most serious problems that the architectural profession and the construction sector will face this century. Growing evidence of the effects of greenhouse gas emissions on the global climate mean that buildings must have greatly reduced energy consumption and be able to adapt to rising temperatures (IPCC, 2007).

Climate change is especially a serious challenge for the architectural profession in the Nordic countries. In Denmark, architects are educated in the beaux-art tradition, with the Schools of Architecture being placed under the Ministry of Culture. This means that artistic concerns relating to design synthesis and spatial disposition play a major role in the profession, whilst an understanding of building physics and engineering sciences has not been seen as relevant. This obviously creates a dilemma, since on the one hand architects have strong artistic roots, where the core competence within the profession is perceived to be a creative design process unhampered by external pressures. On the other hand, the need to adapt to climate change and greatly reduce energy consumption implies that unprecedented changes in building design and function will be necessary over the coming years, demanding a greater understanding of building physics and science.

Just as in the 1930's and 1950's, where the definition of architecture was widened with a new functionalism to include a social and political dimension, and the architectural profession played an important role in developing the welfare state's housing policy (Nygaard, 1984; Lund, 1993), the authors of this paper argue that the understanding of architecture again needs to be widened if the architectural profession is to play an active role in combating climate change. For the architectural profession, not understanding the building physics that form the basis of the energy and climate debate equates to ceding an even larger portion of the construction process to other professionals, thus negating the profession's wider social responsibilities to clients and building users.

Building energy consumption has been radically transformed in Denmark since the 1970's, with a large fall in heating consumption and a continuous rise in electricity consumption. In new buildings it is the total electricity consumption that now dominates the primary energy consumption, whilst heating has been considerably reduced. At the same time, climate change scenarios show that cooling demand will grow in buildings, whilst heat demand can be expected to fall in the future.

The aim of this paper is therefore to develop a new paradigm for zero-energy architecture which learns from past changes in energy consumption, is based upon current social and technological developments, and takes account of future climate change scenarios. The paper consists of four sections:
- The Past: Changes in energy consumption since the first oil crisis in the 1970's.
- The Present: An analysis of the total primary energy consumption in new buildings.
- The Future: The consequences of future climate change on the energy consumption.
- Towards a New Paradigm: A strategy for zero-energy architecture based on functionality, spatiality, materiality and technology.

This paper is focussed on administration and office buildings, since this building typology plays an important role in modern society, reflecting the movement from an industrial society to a knowledge-based society (Gann, 2000), and indicating that social and technological transformation can have a large impact on energy consumption.

This paper has its roots in reflections and experiences, from both research and practice, regarding implementation in Denmark of the European Union Energy Performance of Buildings Directive. This was implemented in the Danish Building Regulations in 2006 by introducing a radically different methodology for calculating building energy performance with the Be06 software developed by the Danish Building Research Institute.

THE PAST

To understand the nature of today's building energy consumption, it is necessary to have an understanding of the historical developments since the 1970's oil crisis. Both the Danish Statistics Agency and the Danish Energy Agency have comprehensive statistical databases relating to the building and energy sectors stretching back to the 1970's, which means that it is possible to carry out a detailed historical analysis of energy consumption.

Total Office Stock

In the years 1975 to 2005 the total population in Denmark has only grown by 7 %. However, there has been a major change in employment patterns, with a very large growth in the knowledge-based economy, especially within the IT, consultancy and service sectors. These changes are reflected in the total floor area of the office stock, which has grown about 55 % between 1975 and 2005. In the same period the total heat consumption for office buildings has only risen about 10 %, whilst the total electricity consumption has risen 160 %. These shifts in energy consumption are illustrated in Figure 1. Despite the growing floor area, Denmark has actually experienced very little growth in the total heat energy consumption in the office stock. This is because existing buildings have been re-furbished, new energy efficient heating systems have been installed, and newer offices have been built to higher standards because of changes in the Building Regulations (Energistyrelsen, 2007).

These changes stand in sharp contrast to the growth in the total electricity consumption, which stems from a large growth in IT-related technologies. Apart from the large growth in electricity consumption to computers and office equipment, the knowledge-based economy has resulted in new business models and work processes with a focus on creativity, innovation and change. This has transformed how office buildings are used, best reflected by the *New Ways of Working* (Rømer, 2001). Architecturally, the consequence has been the design of very deep building typologies with large glass facades, large open office landscapes, and unlit central service zones (Thau, 2001). Typically, these buildings have a considerable demand for artificial lighting, mechanical ventilation and cooling.

New Build Offices

The tendency for falling heat consumption and growing electricity consumption visible since the 1970's is also noticeable when looking at the total energy consumption of new build offices. This can be illustrated by looking at a three-storey office building with a gross floor area of 2.700 m^2, a typology that reflects developments within Danish architectural traditions over the last 30 years (Lund, 2001; Thau, 2001). The analysis compares the historical data for offices' electricity consumption presented above with the total heat consumption for new build offices built in the years from 1975 to 2005, based on the Building Regulations from 1972 and onwards (Boligministeriet, 1972, 1977, 1995), where changes in thermal standards were introduced:

- The total heat consumption, as calculated by the Be06 software, covers space heating and domestic hot water. It is assumed to include typical efficiency losses in the heating system using district heating, and it is assumed that the primary energy conversion factor is 1.0, as prescribed by the new Danish energy regulations.
- The documented total electricity consumption, from Energistyrelsen (2007), covers office equipment, lighting and building services. It is assumed that the primary energy conversion

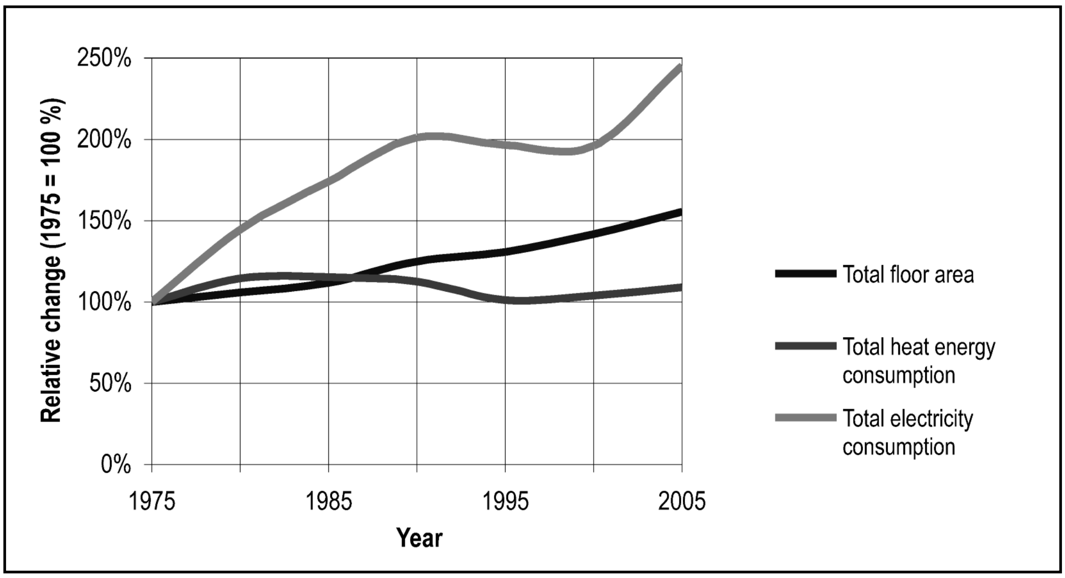


Figure 1: Change in the Danish office stock's total space heating energy consumption, total electricity consumption and total floor area from 1975 to 2005 (1975 = 100 %). References: Danmarks Statistik (1976 – 1982); Danmarks Statistik (2008); Dansk Ejendomsmæglerforening (2007); Energistyrelsen (2007); Hartoft-Nielsen (1992); Sadolin & Albæk (2006).

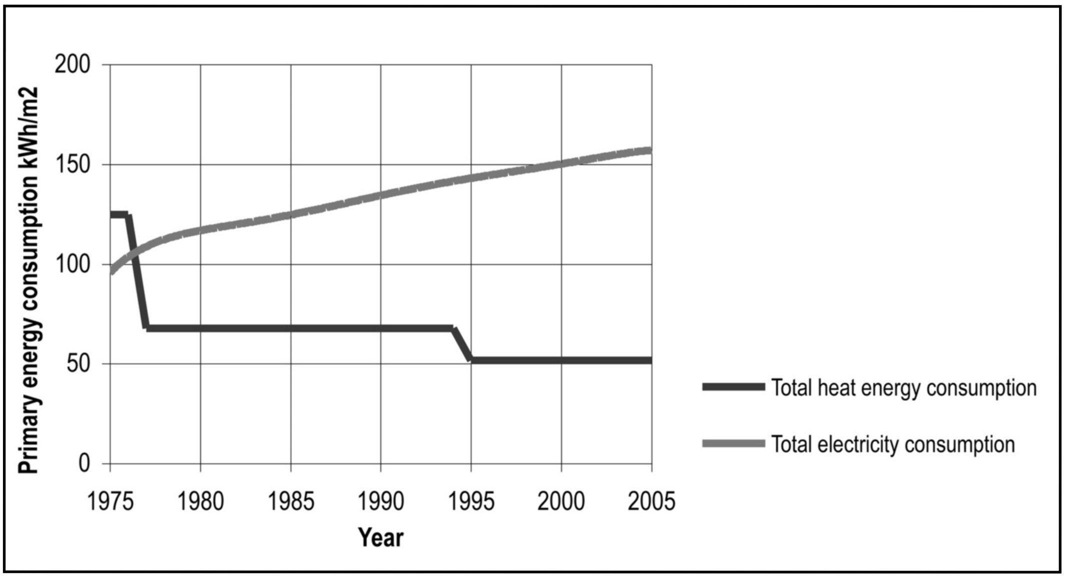


Figure 2:
Change in Danish new build office's total heat consumption and total electricity consumption expressed as primary energy consumption per m^2 floor area from 1975 to 2005.

factor is 2.5, as prescribed by the new Danish energy regulations, and reflecting the large energy loss in the mostly coal-based production of electricity in Denmark.

The results from this analysis are shown in Figure 2, where it is possible to see the effect of the last 30 years' improvements in offices' thermal performance. Whilst the total heat consumption per unit floor area has been reduced by 60 % in the years from 1975 to 2005, the total electricity consumption has risen 55 % per unit floor area. The total electricity consumption, in terms of primary energy, has actually been larger than the total heat consumption for many years.

This analysis shows that the efforts to reduce new offices' space heating demand have been very successful, but these savings have been negated by a growing electricity consumption. This growing electricity consumption can therefore be seen as part of the wider transformation towards a knowledge-based society which industrialised countries have experienced since the 1980's, and where changing perceptions about how buildings are used has come to expression in the fast growth in the use of electrical and electronic equipment (Gann, 2000).

THE PRESENT

The European Union Energy Performance of Buildings Directive (EPBD) sets the common framework for energy savings in the construction and housing sectors (Official Journal of the European Communities, 2003). 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 offices encompass energy consumption to space heating, domestic hot water, lighting, mechanical cooling and building services.
- Problems with overheating during the summer months are also regulated. The equivalent electricity consumption to eliminate temperatures over 26 ^{0}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. 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

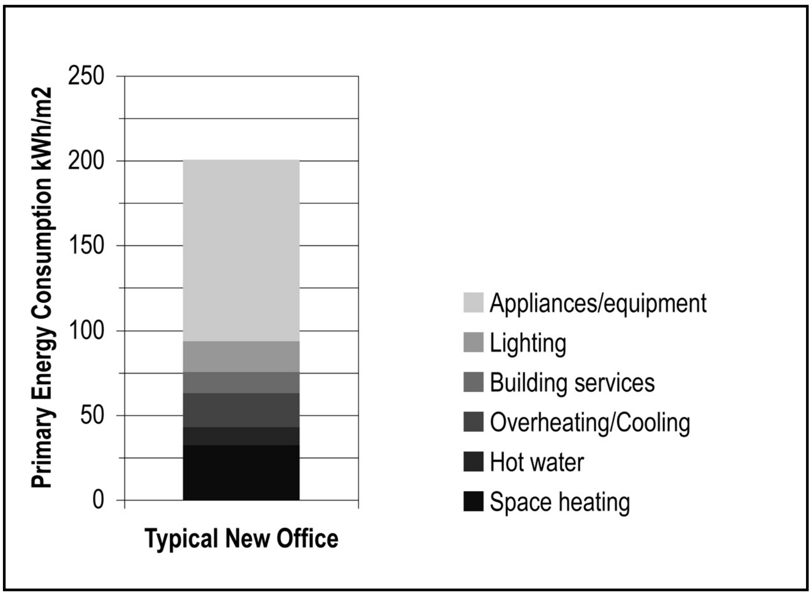


Figure 3: Total primary energy consumption for current Danish new build office expressed as primary energy consumption per m² floor area.

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 Danish regulations for offices do not encompass the electricity consumption for electrical appliances and equipment. However, the growing electricity consumption in offices needs to be seen in relation to the wider transformations from an industrial to a knowledge-based society. Therefore, for the purposes of a balanced and fair comparison of different energy saving strategies, it makes good sense to include the electricity consumption to appliances and equipment in the calculation of the total primary energy consumption and CO_2 emissions (Boardman, 2007).

The total primary energy consumption for the typical three-storey office with a gross floor area of 2.700 m² can be calculated with the Be06 software. The office is based on current standards to meet the new energy regulations' requirements (Marsh et al., 2008), and the remaining electricity consumption is taken from Energistyrelsen (2007). The results, as shown in Figure 3, lead to three overall conclusions:
- It is electricity consumption (consisting of office equipment, lighting, building services and overheating/cooling) that dominates the total primary energy consumption for new build housing, at about 80 % of the total. Heat consumption (consisting of space heating and domestic hot water) is only responsible for about 20 %.
- About 50 % of the total primary energy consumption (consisting of space heating, domestic hot water, building services, overheating/cooling and lighting) is regulated by the new energy regulations. The remaining 50 %, covering electricity consumption to office equipment, is not regulated.
- The electricity consumption for office equipment is the largest component at 50 % of the total primary energy consumption, whilst space heating is only 15 %.

Seen in relation to the previous historical analysis, it can be reasonably argued that new buildings have become better insulated, and that they typically use larger areas of highly insulated glazing. However, there has been a growth in the components of energy consumption which historically have not been regulated, where the electricity consumption and the internal heat gains from office equipment have become larger. This means that the internal energy balance between heat losses and heat loads has shifted in buildings (Orme et al., 2003; Persson et al., 2006). It is now the total electricity consumption, including the summer's cooling demand because of overheating, that dominates new offices' total primary energy consumption, whilst the heating demand has been greatly reduced. Based on known data it is reasonable to assume that the same is true for all other important building types (Marsh et al., 2008).

THE FUTURE

An important factor in Danish energy policy is the need to reduce greenhouse gas emissions because of climate change (Energistyrelsen, 2008). Climate change is expected to give warmer summers and more extreme heat waves around the globe. Whilst the extent of these changes is dependent on the extent of future greenhouse gas emissions, an increase in global temperatures of between 1 and 6 ^{0}C by the end of this century is already expected (IPCC, 2007).

2006 and 2007 were the warmest years ever recorded in Denmark since measurements began in 1874, whilst four of the seven warmest years ever recorded can be found between 2000 and 2007 (Capelin & Jørgensen,

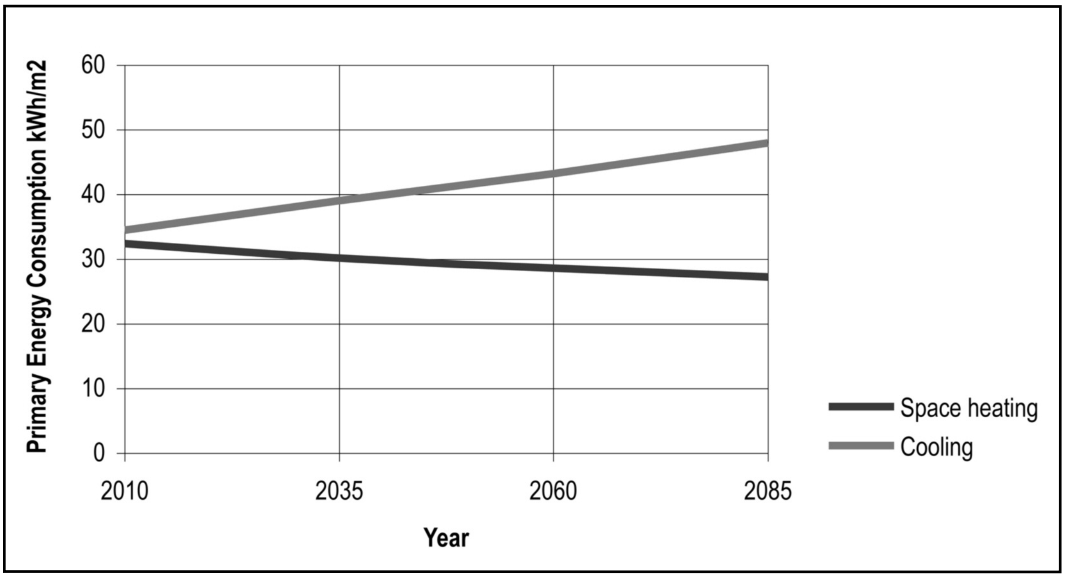


Figure 4:
Change in space heating and cooling for new build offices in relation to the expected climate change from 2010 to 2085 expressed as primary energy consumption per m2 floor area.

2008). From these records it is possible to compare how the climate has changed in recent years in relation to reference weather data used:
- In Denmark the Design Reference Year (DRY) is used in energy calculation programs, and is based on climate data over the fifteen-year period between 1975 and 1989 (Jensen & Lund, 1995). Temperatures over the last 15 years are on average 0.9 ^{0}C higher than the years 1975 to 1989.
- For meteorological purposes the 30-year period from 1961 to 1990 is also used. Temperatures over the last 30 years are on average 0.5 ^{0}C higher than the years 1961 to 1990.

It is therefore reasonable to assume that all new buildings in Denmark are designed on the basis of incorrect climate data that, because of climate change, overestimates the need for space heating and underestimates the need for cooling.

For Denmark, climate change is expected to result in a warmer climate, with climate change scenarios predicting an increase in temperature of up to 3 ^{0}C for both winter and summer conditions in the years up to 2085 (Jørgensen et al., 2006). The Danish Government expects that climate change will result in a reduced demand for space heating in the winter and a greater demand for cooling in the summer in buildings (Regeringen, 2008). This can be illustrated by looking at the typical three storey office built after current standards to meet the new energy regulations' requirements, and calculating the primary energy consumption for heating and cooling with the Be06 software in relation to the expected rise in temperature between 2010 and 2085. It is assumed that mechanical cooling is used to eliminate overheating and ensure thermal comfort, as expected by the Danish Government (Regeringen, 2008). The results, shown in Figure 4, indicate that by 2085 space-heating demand will be reduced 15 %, whilst the primary energy consumption to cooling will be 40 % larger.

Climate change means that offices' total primary energy consumption is expected to rise as the composition of energy consumption changes. The demand for mechanical cooling and therefore electricity consumption will rise, whilst the demand for space heating will fall. These results are supported by a series of similar international studies from comparable countries, which show the same tendencies for all important building types (Frank, 2005; Hacker & Holmes, 2007). The implication of this analysis is that there is a growing need to focus on design strategies and technologies that eliminate the demand for mechanical cooling, whilst also ensuring satisfactory summer thermal comfort, both today and in the future. Such climate change adaptation strategies point towards the utilisation of daylighting design, solar shading, controlled natural ventilation and a high thermal mass to minimise energy consumption and ensure thermal comfort (Hacker et al., 2005).

TOWARDS A NEW PARADIGM

For the Danish architectural profession, there has in many years been an uncritical approach to low energy issues, which in part can be seen to stem from a lack of understanding of building physics and engineering science. This has typically put the architectural profession in a weak position, since the low energy paradigm has traditionally been constructed within the engineering profession's realm. The architectural response in this way becomes filtered and delayed, both in relation to content and delivery. This can, for example, be seen in the architectural perception of passive solar energy, which has for many years received much uncritical coverage promoting the architectural and energy related qualities, but without any serious analysis of whether reductions in energy consumption are delivered (Beim *et al.*, 2002), and this is despite the fact that much research shows that passive solar architecture does not always equate with savings in primary energy in a Nordic context (Marsh *et al.*, 2001; Persson et al., 2006).

This paper has shown that building energy consumption has been radically transformed in Denmark since the 1970's, with a large fall in heating consumption and a continuous rise in electricity consumption. In new buildings it is the total electricity consumption that now dominates the primary energy consumption, whilst heating plays a greatly reduced role. At the same time, climate change scenarios show that cooling demand will grow in buildings, whilst heat demand can be expected to fall in the future.

There is therefore a need to develop a new paradigm for low energy architecture, which learns from developments in the past, is based on today's energy consumption patterns and reflects the future effects of climate change. This new paradigm also needs to reflect the architectural design process, which is characterised by a progression from the generalised to the specific, from rough spatial sketches to detailed construction specifications. Typically, issues relating to functional disposition, spatial quality and built form are decided early in this design process, and it has also been shown that these form related factors have a dominating effect on energy consumption and CO_2 emissions (Marsh *et al.*, 2006). Therefore, a new paradigm can be developed that reflects the progression in the design process, starting with a generalised approach that focuses on architectural form and passive design, and progressing to a more specific focus on technological details. The four cumulative and iterative strategies are:

1 Functionality: Development of user-orientated and functional strategies to reduce energy consumption.

2 Spatiality: The spatial proportioning of the building to improve daylighting and indoor comfort, whilst electricity consumption is reduced.

3 Materiality: Design of structural and constructional elements to reduce energy to heating, cooling and materials.

4 Technology: Integration of energy saving and producing technologies which balance energy saving and renewable energy production.

Functionality

Modern society is 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 clear tendency towards integrating IT infrastructures in new buildings (Marsh, 2008), thereby explicitly encouraging an expected level of IT functionality and electricity consumption. 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.

Traditionally, factors relating to user behaviour have not been integrated in the design process for low energy buildings, since it has not been perceived as possible to control or determine them in the procurement process. However, it has been shown that at least half of new buildings' total primary energy consumption comes from users' electrical equipment, and that issues relating to overheating and indoor comfort are growing in importance because of climate change. There is therefore a need to challenge this traditional approach and develop user-orientated and functional strategies to reduce energy consumption.

Issues relating to indoor comfort and climate are closely related to user perception and building interaction. In a Nordic context, the debate on indoor comfort has been dominated by Fanger's static model of thermal comfort, where user interaction has no affect on comfort. In recent years however, a newer model of adaptive thermal comfort has been developed that integrates behavioural, physiological and psychological factors in how users achieve thermal comfort (Kwok & Rajkovich, 2009), and this is seen as playing a critical role in allowing both users and buildings to adapt to future climate change (Shove *et al.*, 2008). From an architectural viewpoint, the use of adaptive thermal environments, where users can open and shut windows, control daylight distribution and adjust solar shading, have many advantages as strategies that can both deliver reduced energy consumption and greater user satisfaction.

Reducing the energy consumption from electrical equipment and appliances is important because these savings deliver both large reductions in primary energy consumption and reduce unwanted heat emissions and overheating in the summer, which in turn improves thermal comfort and reduces the need for cooling, an important factor in relation to climate change. It is worth noting that construction professionals in Denmark are already involved in the purchase and installation of electrical equipment, reflecting the growth in integrating IT infrastructures in new buildings, but without demands to electricity consumption being made.

By focussing on electrical equipment, it becomes necessary to change building procurement practices, so that factors relating to users' purchase and operation of electrical appliances can be integrated in the design process (Boardman, 2007). By including electricity consumption in this way, it also becomes possible to initiate a broader process of user education and participation, integrating behavioural and technological solutions in reducing energy consumption (Gram-Hanssen & Gudbjerg, 2006).

The new Åparken office building in Kolding, Denmark, (see figure 5), designed by GBL Architects, is a prime example of how functional concerns have been integrated in the low energy strategy, with a very large focus on electricity savings. The electrical installations have been divided into small zones, each of which is individually switchable, and low energy installations have been used, so that electrical equipment can be shut off when not in use and at night, ensuring large savings. At the same time, users have been provided with detailed instruction manuals in how to use the building to save electricity.

Figure 5:
Åparken office building, Kolding, Denmark, GBL Architects (2008). Functional concerns have been integrated in the strategy to reduce the total primary energy consumption, with a very large focus on electricity savings.

Spatiality
With the effects of climate change there is a need to prioritise the architectural design of buildings so that overheating in the summer is avoided. Research has shown that architectural form can play an important role in reducing cooling demands and at the same time in optimising the utilization of natural daylight and minimising the use of artificial lighting (Marsh *et al.*, 2006).

Figure 6
VKR Holdings headquarters, Hoersholm, Denmark, Hvidt & Mølgaard Architects (2007). Spatial proportioning creates high levels of well-distributed daylight. This provides a good working environment, low primary energy consumption, and no need for mechanical cooling.

Traditional low-energy paradigms have focussed on reducing the 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 (Lund, 2001; Thau, 2001).

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 (Baker & Steamers, 2000; Marsh *et al.*, 2006). 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 will be greatly reduced, thereby reducing the cooling demand.

Traditional heat saving paradigms have promoted the use of large areas of south facing glazing to reduce space heating in Danish buildings, also in larger building types such as offices (Radisch & Lading, 2000), and this has resulted in severe problems with overheating. With climate change projections of increasing temperatures and rising cooling demand in the future, it is important to design buildings with a low energy consumption and a good thermal comfort in relation to present and future summer conditions. Glazed areas need therefore to be designed so that their size and distribution is based on the need for daylight in the 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 computer displays, 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 computer display usage, whilst at the same time problems with overheating and cooling demand are eliminated. By consciously utilising daylight from the north, the remaining glazed areas to the east, south and west 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.

The new office building for VKR Holdings in Hoersholm, Denmark, by Hvidt & Mølgaard Architects (see Figure 6), uses spatial proportioning with generous ceiling heights and reduced room depths, together with highly placed windows and rooflights, to create high daylight levels with very even distribution. This provides a good working environment in rooms that also are naturally ventilated, giving low primary energy consumption and no need for mechanical cooling.

The office building designed by KHR Architects for B&O in Struer, Denmark, has consciously worked with principles to maximise the amount of northlight in the office spaces, whilst limiting direct sunlight and overheating from the south. This has been achieved by orientating the larger glazed areas to the north, and the smaller areas to the south, as shown in figure 7.

Figure 7:
B&O headquarters, Struer, Denmark, KHR Architects (1998). The conscious use of northlight to create good visual comfort, minimise overheating, and utilise natural ventilation in the office spaces.

Materiality

For the architectural profession, the use of materials to minimise energy consumption has focussed on reducing heat consumption, but concerns regarding climate change have led to a larger focus on reducing overheating and cooling demand. It is also important to take account of the embodied energy, that is the energy used to extract, produce and transport building materials throughout their life cycle (Marsh *et al*., 2001).

Buildings in Denmark have much greater levels of thermal insulation than for 30 years ago, as discussed earlier. The improved insulation of the building fabric can play a role, but there needs to be found a balance, since very large insulation thicknesses have been shown not to give very large energy savings because other contradictory factors begin to play a more important role. Amongst others, the useable floor area becomes reduced, the quality and quantity of daylight can be impaired by the very deep window reveals, and the embodied energy of the extra materials can almost equal the heat saving, meaning that with current insulation technologies it is difficult to justify insulation thicknesses greater than 500 mm (Marsh *et al*., 2006).

Figure 8:
Badenova office building, Offenburg, Germany, by Lehmann Architects (2006). The use of phase change materials, natural daylighting and natural ventilation give a very low primary energy consumption without traditional HVAC solutions.

Developments in office design show a clear tendency towards large, open plan spaces with very few internal obstructions, and where acoustic requirements often dictate the use of suspended ceilings (Rømer, 2001), meaning that the thermal mass of many modern buildings has been considerably reduced. Since a high thermal mass acts to stabilise the indoor climate, it can be argued that this development has contributed to the rising comfort problems and growing cooling demand in new offices. To counteract this development, the use of so-called phase change materials has become a relevant option in modern buildings. Phase change materials are able to absorb excess heat during the day and emit it again at night, thus reducing overheating and the need to use mechanical cooling. The phase change materials consist of small wax capsules that can be mixed with gypsum in the production of plasterboard, allowing for a thermal mass in lightweight materials (Schossig *et al.,* 2005). The Badenova office building in Offenburg, Germany, by Lehmann Architects (see Figure 8), shows how an architecturally sensitive approach to phase change materials, natural daylighting and natural ventilation can give a very low primary energy consumption without the use of traditional HVAC solutions.

The architectural strategy for the design of structural and constructional elements therefore needs to be optimised to reduce energy to heating, cooling and material production. This can be achieved by designing external walls and roof as lightweight and highly insulated elements, whilst loadbearing walls and floors can be designed as heavyweight concrete elements, which are exposed to the air if possible. Where necessary, lightweight phase change materials can be used to give extra thermal mass.

Technology

There has been a rapid growth in the extent of building services in modern buildings, and this is expected to continue in the future, partly due to the previously discussed technological and social changes relating to the knowledge-based economy, and partly because of the larger focus on energy and environmental concerns in the construction sector (Marsh, 2008). With the building's total primary energy consumption minimised by the optimisation of architectural form in the preceding strategies, solutions relating to buildings' energy saving and producing technologies need to be optimised in relation to future climate change and energy supply scenarios in the movement towards zero-energy buildings.

In zero-energy buildings, energy savings are used to ensure a low total primary energy consumption, which is then met or exceeded on a yearly basis by production from renewable energy sources (Torcellini *et al.*, 2006). The important role that zero-energy buildings are expected to play in the future can be seen in the fact that both the new draft revision of the EPBD and the new Danish Government strategy for effective energy use in buildings propose the development of definitions and targets for zero-energy buildings (Commission of the European Communities, 2008; Regeringen, 2009).

An important aspect of zero-energy buildings is the need to develop renewable energy strategies, whether they either are building integrated or more centralized urban systems, and to integrate them into the wider energy supply system (Dunster *et al.*, 2007). This implies the need for strategic considerations in relation to the interplay between architecture, urban design and energy planning over a long time span.

Building integrated renewable energy systems typically involve the use of large areas of photovoltaic cells to electricity production and solar panels to heat production, which again raises considerable architectural and urban design issues. The use of these solutions opens up new architectural challenges in the development of intelligent façade solutions that integrate daylight, ventilation and indoor comfort control with active solar shading and photovoltaic electricity production. The use of new transparent photovoltaic solutions integrated into glazing components can be seen to create many interesting architectural potentials in relation to how daylight is filtered, controlled and perceived in different spaces (Hansen *et al.*, 2008).

In the new Green Lighthouse office building for the University of Copenhagen, by CCO Architects, and which was completed in time for the COP15 Climate Summit (see Fig-ure 9), a careful balance of broad energy savings combined with building integrated energy production from photovoltaic cells and solar panels has created the first zero-energy office building to be built in Denmark.

Figure 9:
Green Lighthouse office building, University of Copenhagen, CCO Architects (2009). Low primary energy consumption combined with building integrated energy production has created the first zero-energy office building in Denmark, which was completed for the COP15 Climate Summit.

CONCLUSIONS

This paper has argued that the understanding of architecture again needs to be widened if the architectural profession is to play an active role in combating climate change. For the architectural profession, a lack of understanding of the building physics that form the basis of the energy and climate debate may result in ceding an even larger portion of the construction process to other professionals, which can be seen as a negation of the architectural profession's wider social responsibilities.

This paper has shown that for office buildings in Denmark, heat consumption has been considerably reduced over the last 30 years, and as a reflection of the growth of the knowledge society, it is now electricity consumption that dominates new buildings' total primary energy consumption. At the same time, future climate change will result in a larger demand for cooling in the summer and a reduced demand for heating in the winter. Research shows that the same tendencies for the past, present and future are also applicable to all important building types.

The architectural design process is characterised by a progression from the generalised to the specific, where important energy related factors such as functional disposition, spatial quality and built form are decided early in the process. With this background, a new paradigm for zero-energy architecture has been developed using four cumulative and iterative

strategies, starting with a generalised approach that focuses on architectural form and passive design, and progressing to a more specific focus on technological details.
By starting with issues relating to functionality and spatiality, the new paradigm uses the architectural profession's core competences in relation to design synthesis and spatial disposition as the driving force to create buildings that have low primary energy consumption, good daylighting and indoor comfort, and are adapted to future climate change. From this basis, the new paradigm progresses to issues relating to materiality and technology, where more specific, technical factors are integrated, and where energy savings and renewable energy production is optimised in relation to future climate change and energy supply scenarios for zero-energy architecture.

The use of this strategic approach allows the architectural profession to put architecture and design at the forefront of the debate on energy and climate in the construction sector. This means that architectural design can be used as a driving force in the movement towards zero-energy buildings, and this widens the understanding of architecture as an active player in combating climate change, thus supporting the profession's wider social responsibilities to clients and building users.

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.

AUTHORS

Rob Marsh
Senior Researcher, Architect MAA, PhD
Danish Building Research Institute, Aalborg University, Denmark
rom@sbi.dk

Vibeke Grupe Larsen
Consultant, Architect MAA
Vglcph aps., Denmark
vgl@vglcph.dk

Jake Hacker
Building Physicist, PhD
Arup, Denmark
jake.hacker@arup.com

LITERATURE

AGGERHOLM, S. & GRAU, K. (2005) *Buildings' Energy Demand – Pc-programme and calcu-lation guide. SBi-Direction 213* [in Danish], Danish Building Research Institute (Statens Byggeforskningsinstitut), Hoersholm.

BAKER, N. & STEEMERS, K. (2000) *Energy and Environment in Architecture*, E&FN Spon, London.

BAUMANN, Z. (2000) *Liquid Modernity*, Polity Press, Cambridge.

BEIM, A., LARSEN, L. & MOSSIN, N. (2002) *Ecology and Architectural Quality* [in Danish], Royal Academy of Arts School of Architecture Press (Kunstakademiets Arkitektskoles Forlag), Copenhagen.

BOARDMAN, B. (2007) Examining the carbon agenda via the *40% House* scenario. *Building Research & Information,* 35(4), 363-378.

BOLIGMINISTERIET (1972) *Building Regulations for Urban and Rural Areas* [in Danish], Ministry of Housing (Boligministeriet), Copenhagen.

BOLIGMINISTERIET (1977) Building Regulations [in Danish], Ministry of Housing (Boligministeriet), Copenhagen.

BOLIGMINISTERIET (1995) *Building Regulations* [in Danish], Ministry of Housing (Boligministeriet), Copenhagen.

CAPPELEN, J. & JØRGENSEN, B.V. (2008) *Danish Weather Since 1874. Technical Report 08-02* [in Danish], Danish Meteorological Institute (Danmarks Meteorologiske Institut), Copenhagen.

COMMISSION OF THE EUROPEAN COMMUNITIES (2008) *Proposal for a Directive of the Euro-pean Parliament and the Council on the energy performance of buildings*, Brussels.

DANMARKS STATISTIK (2008). *The Danish Energy Accounts*. Danish Statistics Agency (Danmarks Statistik), Copenhagen. Localised on 2008.06.25 at: http://www.dst.dk:80/HomeUK/Statistics/ofs/NatAcc/IOTABLES/Energy.aspx

DANMARKS STATISTIK (1976–1982) *Statistical Yearbook 1976 – 1982* [in Danish], Danish Statistical Agency (Danmarks Statistik), Copenhagen.

DANSK EJENDOMSMÆGLERFORENING (2007). *Oline-Office Market Statistics* [in Danish], Dan-ish Association of Chartered estate Agents (Dansk Ejendomsmæglerforening) Copen-hagen.

DUNSTER, B., SIMMONS, C. & GILBERT, B. (2007) *The ZEDbook*, Taylor & Francis, London.

ENERGISTYRELSEN (2007) *Energy Statistics 2006* [in Danish], Danish Energy Agency (Ener-gistyrelsen), Copenhagen.

ERHVERVS- OG BYGGESTYRELSEN (2008) *Building Regulations* [in Danish], National Agency for Enterprise and Construction (Erhvervs- og Byggestyrelsen), Copenhagen.

FRANK, T. (2005) Climate Change Impacts on Building Heating and Cooling Energy De-mand in Switzerland. *Energy and Buildings*, **37**(11), 1175-1185.

GANN, D. (2000) *Building Innovation: Complex Constructs in a Changing World*, Thomas Telford, London.

GRAM-HANSSEN, K. & GUDBJERG, E. (2006) *Standby consumption in households - by means of communication or technology?*, in: *Proceedings of the 2006 ACEEE Summer Study on Energy Efficiency in Buildings - Less is More: en route to zero energy build-ings.* American Council for an Energy-Efficient Economy, Washington D.C., pp. 33-44.

HACKER, J., HOLMES, M., BELCHER, S. & DAVIES, G. (2005) *Climate Change and the Indoor Environment: Impacts and Adaption. CIBSE TM36,* Chartered Institute for Building Services Engineers, London.

HACKER, J. & HOLMES, M. (2007) Thermal Comfort: Climate Change and the Environmental Design of Buildings in the United Kingdom. *Built Environment*, **33**(1), 97-114.

HANSEN, E.K., HILBERTH, T. & MUNK, L. (2008) *Light + Energy + Architecture: potentials in transparent photovoltaic cells* [in Danish], Aarhus School of Architecture Publishers (Arkitektskolens Forlag), Aarhus

HARTOFT-NIELSEN, P. (1992). *Office Development 1980-90 and Future Planning in Greater Copenhagen* [in Danish], Ministry of the Environment, National Planning Agency (Mil-jøministeriet, Planstyrelsen), Copenhagen.

IPCC (2007) Climate Change 2007: *The Physical Science Basis. Summary for Policy-makers*, Intergovernmental Panel on Climate Change Secretariat, Geneva.

JENSEN, J.M. & LUND, H. (1995) *Design Reference Year, DRY – a new Danish reference year. Bulletin No. 281* [in Danish], Laborotory for Heat Insulation/Technical University of Denmark (Laboratoroet for Varmeisolering/Danmarks Tekniske Universitet), Lyngby.

JØRGENSEN, A.M., CHRISTENSEN, A.B. & MAY, W. (2006) *Climate Change Scenarios for Denmark. Project Report* [in Danish], Danish Meteorological Institute (Danmarks Meteorologiske Institut), Copenhagen.

KWOK, A. & RAJKOVICH, N. (2010) Addressing Comfort in Climate Change Standards. *Building and Environment*, **45** (1), 18-22].

LESLIE, R.P. (2003) Capturing the daylight dividend in buildings: why and how? *Building and Environment*, **28**(2), 381-385.

LUND, N-O. (1993) *Nordic Architecture* [in Danish], Danish Architectural Press (Arkitektens Forlag), Copenhagen.

LUND, N-O. (2001) Break Open the Boxes [in Danish]. *Arkitektur DK,* **45**(4), 256-261.

MARSH, R. (2008) Future Directions for Building Services Technologies in Denmark, in: *I3CON Industrialised, Integrated Intelligent Construction, First International Conference, May 2008*. Loughborough University, Loughborough.

MARSH, R., LARSEN, V.G., LAURING, M. & CHRISTENSEN, M. (2006) *Architecture and Energy* [in Danish], Danish Building Research Institute (Statens Byggeforskningsinstitut), Hoersholm.

MARSH, R., LARSEN, V.G. & HACKER, J. (2008) *Buildings Energy Climate: Towards a New Paradigm* [in Danish], Danish Building Research Institute (Statens Byggeforskningsinsti-tut), Hoersholm.

MARSH, R., LAURING, M. & PETERSEN E.H. (2001) Passive Solar Energy and Thermal Mass: The implications of environmental analysis. *Architectural Research Quarterly,* **5**(1), 79-89.

NYGAARD, E. (1984) *A Roof Over One's Head* [in Danish], Danish Architectural Press (Arkitektens Forlag), Copenhagen.

Official Journal of the European Communities (2003) DIRECTIVE 2002/91/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 16 December 2002 on the energy performance of buildings, *Official Journal of the European Communities,* (1), 65-70.

ORME, M., PALMER, J. & IRVING, S. (2003) Control of Overheating in Well-Insulated Housing, in: *Proceedings of ASHRAE/CIBSE Conference (24-26 September) – Building Sustainability, Value & Profit. ISBN: 190328743X.*

PERSSON, M., ROOS, A. & WALL, M. (2006) Influence of window size on the energy balance of low energy houses. *Energy and Buildings,* **38**(3), 181-188.

RADISCH, N. & LADING, T. (2000) *Solar energy. The ecology of large buildings* [in Danish], Danish Center for Urban Ecology (Dansk Center for Byøkologi), Aarhus.

REGERINGEN (2008) *Strategy for Climate Change Adaption in Denmark* [in Danish], Danish Energy Agency (Energistyrelsen), Copenhagen.

REGERINGEN (2009) *Strategy for the Reduction of Energy Consumption in Buildings* [in Danish], Danish Enterprise and Construction Authority (Erhvervs- og Byggestyrelsen), Copenhagen.

RØMER, M. (2001) Office Design [in Danish]. *Arkitektur DK*, **45**(4), 236-243.

SADOLIN & ALBÆK (2006) *Copenhagen and Malmoe Property Market Report 2006*. Sadolin & Albæk, Copenhagen.

SCHOSSIG, P., HENNING, H., GSCHWANDER, S. & HAUSSMANN, T. (2005) Micro-encapsulated phase-change materials integrated into construction materials. *Solar Energy Materials and Solar Cells*, **89**(2-3), 297-306.

SHOVE, E., CHAPPELLS, H., LUTZENHISER, L. & HACKETT, B. (2008) Comfort in a lower carbon society. *Building Research & Information,* **36**(4), 307-311.

THAU, C. (2001) In the black box [in Danish]. *Arkitekten*, **103**(13), 15-16.

TORCELLINI, P., PLESS, S., DERU, M. & CRAWLEY, D. (2006) Zero Energy Buildings: A Critical Look at the Definition, in: *Proceedings of the 2006 ACEEE Summer Study on Energy Efficiency in Buildings - Less is More: en route to zero energy buildings*. American Council for an Energy Efficient Economy, Washington D.C., pp. 417-429.