Daylight and Energy Analysis Using an Integrated Software System

J. Christoffersen, C.E. **K. Johnsen, C.E.** **J.E. Christensen, Ph.D., C.E.**

ABSTRACT

This paper describes a powerful set of computer tools for building design and for the analysis of daylighting, lighting, and the thermal performance of buildings. A thorough study of the energy required for electric lighting and of the saving potential of daylighting has been carried out. The combined effect of daylighting and artificial lighting on the energy balance and on the thermal indoor climate is also examined.

The study may be seen in the background of the Brundtland Report, "Our Common Future." The Danish government has defined short- and long-term goals for the Danish energy policy. In the report "Energy 2000" (Energiministeriet 1990), these goals are expressed as 25% energy savings in the Building Code of 1993 and 50% energy savings in the Building Code of 2000.

The results of the study indicate possible lighting energy savings between 30% and 60% by the use of an artificial lighting system that responds to the daylight input through typical side windows.

INTRODUCTION

The interest in using energy-efficient daylighting systems and control strategies in modern commercial buildings has increased over the last 10 years. For this reason, the International Energy Agency's (IEA) TASK XI, Passive and Hybrid Solar Commercial Buildings, was started in 1986 as part of the Solar Heating and Cooling Program. The purpose of TASK XI was to strengthen the development and practical use of passive and hybrid solar energy solutions in commercial buildings (Hastings et al. 1992). As a follow-up to the daylighting work in TASK XI, the IEA's TASK XII, Building Energy Analysis and Design Tools for Solar Applications, established the Daylighting Model Development Working Group. Within this group, LESO-PB, Switzerland developed ADELINE (Compagnon et al. 1992), an Advanced Day- and Electric Lighting Integrated New Environment (see Figure 1). ADELINE is built around SUPERLITE (LBL 1985) and RADIANCE (Larson 1991; Ward 1990), developed by a U.S. laboratory. A German institute has developed the SUPERLINK program (Szerman 1990) between SUPERLITE and thermal analysis programs. The thermal analysis program used in this paper is TSBI3 (Thermal Simulation of Buildings and Installations) from a Danish institute (Johnsen et al. 1991).

A short description of the programs will follow in the next sections, but only the left part of the ADELINE system chart in Figure 1 will be discussed.

DESCRIPTION OF DESIGN TOOLS

In designing energy-efficient buildings, it is essential that professionals use tools that can simulate the complex and dynamic behavior of buildings under realistic conditions of use and operation. This paper examines sensitivity studies of improved U-values and reduced solar transmission for windows. Additionally, the computer tools in ADELINE analyze the effect of daylight on energy consumption in buildings.

The Integrated Software System

ADELINE is an integrated daylighting infographic environment between a CAD software (Green et al. 1989) and the daylight design tools SUPERLITE and RADIANCE.

ADELINE can solve both natural and artificial lighting problems for simple and complex spaces. This system allows the user to produce innovative and reliable designs based on photometric, geometric, climatic, optic, and human responses, all taken into account to perform daylighting and artificial light simulations.

The ADELINE system is connected to several thermal analysis systems (TSBI3, SUNCODE, and DOE 2.1D) and the

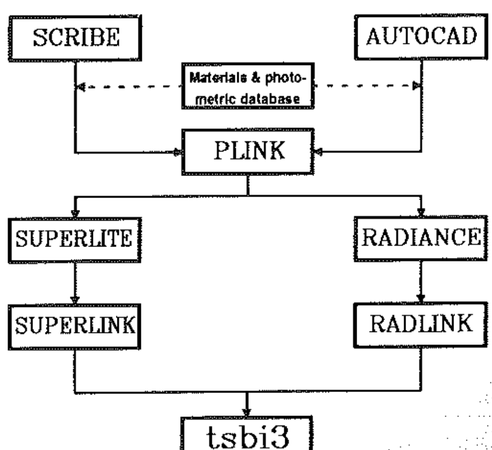

Figure 1 *Flow-chart of the ADELINE system. (Note: All programs except RADIANCE [UNIX system] run under MS-DOS system.)*

Jens Christoffersen is a research scientist with the Danish Building Research Institute and **Kjeld Johnsen** is a research scientist with Esbensen Consulting Engineers, both in Denmark. **Jørgen Erik Christensen** is a professor with Narvik Institute of Technology, Norway.

intention of the work in TASK XII is to integrate all programs under a common shell, such as the operating system WINDOWS environment for personal computers.

The Daylight Program

SUPERLITE is a daylight program for predicting daylight illuminance distribution in buildings. The program is well validated and can be used for simulation of the complex building geometries frequently found in the built environment, including daylighting techniques and shading from external obstructions, and for predicting daylight illuminance distribution in buildings with either natural and/or artificial lighting.

As output one has daylight factors, hourly illuminances on work surfaces, and/or luminances of indoor or outdoor surfaces. However, the program only treats standard CIE clear or overcast skies and not real weather conditions. The calculation method is the flux transfer method including the Monte Carlo method for direct illumination on external surfaces and numerical integration for direct illumination on indoor surfaces and work planes.

The Link Program

SUPERLINK has been developed to analyze the energy-saving potential of artificial lighting by utilization of daylight for different control strategies. SUPERLINK produces data sets of illuminances on the work surface based on three CIE standard sky types: overcast sky, clear sky without sun, and clear sky with sun, thus producing a mean sky (Aydinly 1981). The program calculates the hourly internal heat load from artificial lighting in Btu (Wh). The value is zero during hours with no work or when there is a sufficient amount of daylighting available. In other cases, the heat load corresponds to the maximum power consumption of lamps or to a fraction of it, depending on the lighting control strategy (on/off, dimming). As a result, hourly demands for artificial lighting over the whole year are produced and can be used as input to thermal simulation programs.

Energy Analysis Program

The thermal simulation program TSBI3 was developed in Denmark for research and commercial use. The program has been used in a number of international collaborative projects under the IEA (International Energy Agency) and EEC (European Community).

Using hourly weather data (various file formats), TSBI3 can simulate most commercial buildings, including HVAC equipment, for analysis of the thermal working environment, energy consumption, systems and control functions, energy-saving measures, and the utilization of passive solar energy (see Figure 2).

The model for the nonstationary heat conduction through walls is based on an implicit difference method with dynamic determination of the needed number of thermal nodes and the optimum time step (30 minutes or less).

The program has been validated against measured data from test houses, e.g., the Canadian Direct Gain Test Box and some national projects. Good agreement has also been found by comparison with other programs, e.g., DOE-2, SUNCODE/SERI-RES, BLAST.

TSBI3 uses an interactive system of menus that reflects the structure of the program. In order to keep track of all data relations of the input, the menus in the program are designed to overlap each other, with the primary level to the left going to the right (Figure 3). The menus are manipulated by mouse and keyboard with an on-line help facility and access to direct data documentation on the screen. A new version is being developed to run under a commercial window-driven interface, using geometrical input from a CAD system.

The output from the program provides indoor temperature and humidity, energy balances, heating and cooling demands, internal loads, solar gains, infiltration, venting by opening windows, ventilation, heat loss by transmission, electric lighting, shading conditions, solar irradiation on the facades, etc. All the results can be written at different levels on an hourly, daily, weekly, monthly, or yearly basis—either on the screen, to a printer, or to a file for later processing. It is possible to choose between tabular and graphical output.

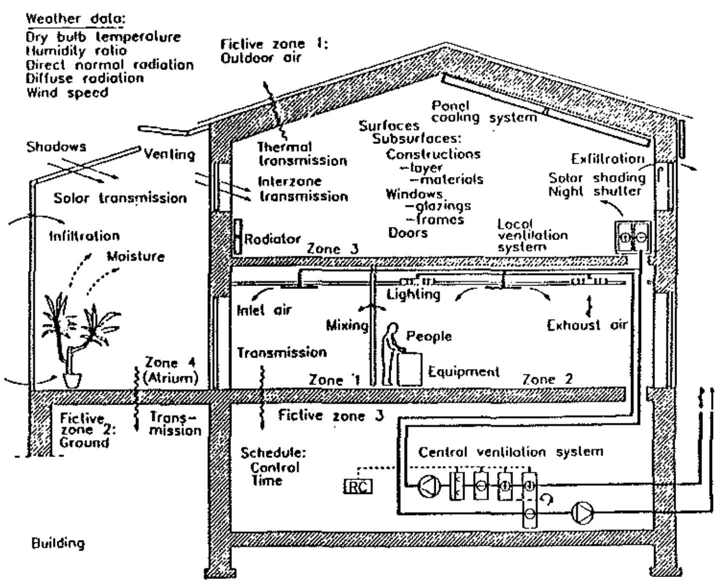

Figure 2 *Schematic drawing of room model showing the program's modules of calculations.*

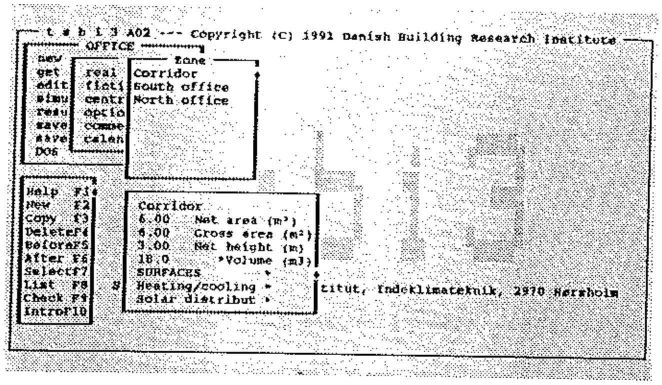

Figure 3 *Example of the menu in* TSBI3 *with the primary level to the left.*

Integration of TSBI3 in the COMBINE Project COMBINE (COmputer Models for the Building INndustry in Europe) is a step toward European development of an intelligent integrated building design system (IIBDS) through which the energy, services, functional, and other performance characteristics of planned buildings can be modeled and analyzed. The aim of COMBINE is to develop a conceptual basis for a future integration of software used in building design in the form of a common conceptual data model, rather than a design system itself. The integrated data model (IDM) will provide a common base for the exchange of building data between different design tools. TSBI3 is already prepared for data exchange with the IDM.

Integration of Daylight Analysis into TSBI3 The ADELINE system offers new possibilities for the integration of analysis of natural daylighting, artificial lighting, lighting control strategies with energy analysis, and thermal performance of buildings. TSBI3 imports the output data of hourly power needed for artificial lighting from SUPERLINK as an alternative to the more simple schedule for the artificial lighting system and lighting control system integrated in TSBI3 (Christensen and Christoffersen 1991a,b).

MAIN BUILDING DATA FOR THE TEST EXAMPLE

A module of an office is set up to calculate the impact of combined daylighting and artificial lighting on the thermal balance of a typical office building. The office is a 258.1-ft^2 (24-m^2) module and the room's width and depth are 13.1 ft (4.0 m) by 19.7 ft (6.0 m). The room's height is 9.8 ft (3.0 m) with a sill height of 3.9 ft (1.2 m) (see Figure 4 and Table 1).

For this office room, a detailed analysis has been done for three different levels of U-values referring to the 1982 Danish Building Code (DK-BC) (Danish Ministry of Housing 1983; DSCCEME 1986), expected U-values for the DK-BC after 1993, and a realistic level for the DK-BC in the next century. The window area in the base case is 15% of the floor area based on the DK-BC 1982.

Performed Simulations

The simulation results presented are for a specific office module with fixed boundary conditions. They are meant to be used as an indication only and therefore should not be uncritically transferred to any other specific case.

The results indicate how the different parameters contribute to the overall building energy balance, including the role of daylighting. In practice, visual comfort and glare play a role in a real setting, but these were not studied specifically. Glare, however, is not expected to occur often in the simulated situation, as venetian blinds were assumed to be activated when the radiation transmitted through the window exceeded 79.4 Btu/(h·ft^2) (150 W/m^2). The blinds were assumed to be adjustable lamellae, which can be oriented to remove glare.

Offices in Denmark are seldom supplied with mechanical cooling and therefore this has been omitted from the study of this paper. Analysis of the temperature level in the office indicates no overheating problems (tendencies to these problems are solved by natural ventilation and blinds).

The greater window area in Table 2, for Building Codes 1993 and 2000 (rooms facing south), is a compensation for the reduced light transmission of the glazing. This will automatically increase the heating consumption and transmission heat losses, but it will also increase the daylight illuminance and distribution and improve visual comfort.

RESULTS

Tables 3 and 4 indicate the consumed energy in Btu/ft^2·y (kWh/m^2·y) for lighting, heating, heating plus lighting, a "cost index" for heating and lighting, and the percentage increase or decrease relative to the base case (DK-BC 1982, etc.) for the daylight strategies considered. The percentage savings are shown in relation to the base case assuming no daylighting and the general lighting and task lighting switched on all day. The energy consumption

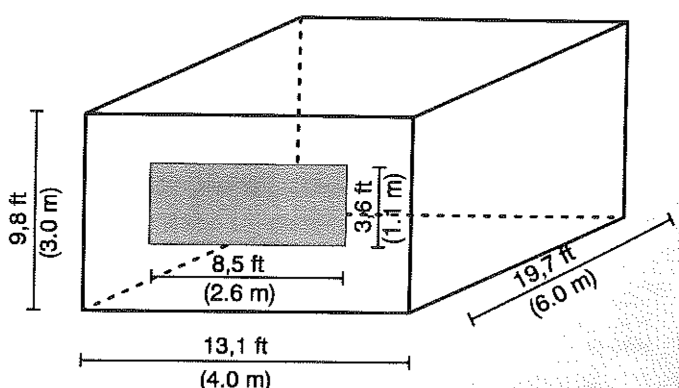

Figure 4 *The geometry for the office module used in the simulations.*

TABLE 1
Main Design Data for SUPERLITE, SUPERLINK, and TSBI3

MODULES	Building Code 1982	Building Code 1993	Building Code 2000
OFFICE, L x W x H	19.7 x 13.1 x 9.8 ft (6 x 4 x 3 m)		
Weather Data	Danish Test Reference Year (TRY)		
Occupancy Profile (working hours)	8 am - 5 pm, 5 days a week		
SURFACES			
Exterior Wall, U-value Btu/(h·ft²·°F) (W/m² K)	0.062 (0.35)	0.053 (0.30)	0.044 (0.25)
Interior Wall, U-value Btu/(h·ft²·°F) (W/m² K)	0.070 (0.40)	0.070 (0.40)	0.070 (0.40)
Roof, U-value Btu/(h·ft²·°F) (W/m² K)	0.035 (0.20)	0.035 (0.20)	0.026 (0.15)
Floor, U-value Btu/(h·ft²·°F) (W/m² K)	0.053 (0.30)	0.035 (0.20)	0.035 (0.20)
WINDOW			
Window area ft² (m²)	44,1 (4.1)	44,1 (4.1)	44,1 (4.1)
Glazing area ft² (m²)	30,8 (2.9)	30,8 (2.9)	30,8 (2.9)
Window U-value Btu/(h·ft²·°F) (W/m² K)	0.51 (2.9)	0.32 (1.8)	0.16 (0.9)
Window Transmission Sun (%)	76	69	51
Window Transmission Light (%)	80	63	55
Blinds activated if transmitted radiation exceeds	79,4 Btu/(h·ft²) (150 W/m²)		
Shading coefficient	0.3		
INDOOR TEMPERATURE			
Set-point during work hours	68,0 °F (20 °C)		
Set-point outside work hours, weekends included	62,6 °F (17 °C)		
INFILTRATION			
during work hours	0.25 ac/h		
outside work hours, weekends included all year	0.12 ac/h		
MECHANICAL VENTILATION			
during work hours	2.0 ac/h		
outside work hours, weekends included all year	0.5 ac/h		
Heat recuperation	60%		
INTERNAL LOAD			
People, during work hours	512 Btu/h (150 W)		
Equipment, during work hours	819 Btu/h (240 W)		
Lighting:			
Local spots (on during working hours)	68 Btu/h (20 W)		
General lighting (Controlled)	819 Btu/h (240 W)		
Lighting Control	On/off and Dimming		
Desired Illuminance level on work surface	18,6 fc (200 lx)		
Luminous Efficacy on work surface	(19.3 lm/W)		
NATURAL VENTILATION			
If indoor temp. exceeds 77°F (25°C) during working hours	3 h^{-1}		

for the different orientations is added together (east values multiplied by two).

The results show that if daylighting is properly utilized as work surface illuminance, between 22% and 54% of lighting (L) energy may be saved. However, since Denmark is far north (altitude 56°) with a long heating season, some of the saved lighting energy results in an increased energy consumption for heating; but the studies also show that the energy for heating can be reduced by improved glazings and insulation (as proposed in the new Danish Building Code).

The values in Table 3 show heating (H); lighting (L); the sum of the two sources, heating+lighting (H+L); and a "cost index" (H+2*L) based on the use of natural gas for heating (current Danish energy rates). Two lighting control systems have been simulated (only for general lighting): (1) light switch on/off and (2) dimming compared with the nondaylit base case with electric lights on during the entire time of occupancy.

The results in Tables 3 and 4 show possible heating energy savings up to 26% in the case of Building Code 1993 and up to 50% in the case of Building Code 2000. In

TABLE 2
The Different Cases in the Study, with Variable Window Percentage

OFFICE	North	South	East
Building Code 1982 (BC 1982)	15%	15%	15%
Building Code 1993 (BC 1993)	15% 15%	15% 20%	15% 15%
Building Code 2000 (BC 2000)	15% 15%	15% 25%	15% 15%

TABLE 3
Percentage Savings (%) for Different Building Codes Compared to the Base Case (DK-BC 1982)

CASE (15% Window Area)	STRATEGY	HEATING (H)		LIGHTING (L)		H + L		H + 2*L	
DK-BC 1982 Btu/ft^{2}y (kWh/m^{2}y)	on	256997 (75.3)	0%	86689 (25.4)	0%	343686 (100.7)	0%	430375 (126.1)	0%
DK-BC 1993 Btu/ft^{2}y (kWh/m^{2}y)	on	190444 (55.8)	26%	86689 (25.4)	0%	277133 (81.2)	19%	363822 (106.6)	15%
	on/off	202730 (59.4)	21%	61433 (18.0)	29%	264163 (77.4)	23%	325596 (95.4)	24%
	dimming	211604 (62.0)	18%	40273 (11.8)	54%	251877 (73.8)	27%	292150 (85.5)	32%
DK-BC 2000 Btu/ft^{2}y (kWh/m^{2}y)	on	128328 (37.6)	50%	86689 (25.4)	0%	215017 (63.0)	37%	301706 (88.44	30%
	on/off	136519 (40.1)	47%	67577 (19.8)	22%	204096 (59.8)	41%	271673 (76.6)	39%
	dimming	147099 (43.1)	43%	43686 (12.8)	50%	190785 (55.9)	44%	234471 (68.7)	46%

TABLE 4
Percentage Savings (%) for Variable Window Area Compared to Base Case (DK-BC 82, 15% Window Area)

CASE (Var. Windows Area rooms)	STRATEGY	HEATING (H)		LIGHTING (L)		H + L		H + 2*L	
DK-BC 82 Btu/ft^{2}y (kWh/m^{2}y)	on	256997 (75.3)	0%	86689 (25.4)	0%	343686 (100.7)	0%	430375 (126.1)	0%
DK-BC 93 (20% window area) Btu/ft^{2}y (kWh/m^{2}y)	on	191126 (56.0)	26%	86689 (25.4)	0%	277815 (81.4)	19%	364504 (106.8)	15%
	on/off	207167 (60.7)	19%	58703 (17.2)	29%	265870 (77.9)	23%	324573 (95.1)	25%
	dimming	216041 (63.3)	16%	38556 (11.3)	54%	254597 (74.6)	26%	293153 (85.9)	32%
DK-BC 2000 (25% window area) Btu/ft^{2}y (kWh/m^{2}y)	on	129693 (38.0)	50%	86689 (25.4)	0%	216382 (63.4)	37%	303071 (88.8)	30%
	on/off	139249 (40.8)	46%	62713 (18.4)	22%	201962 (59.2)	41%	264675 (77.5)	39%
	dimming	148805 (43.6)	42%	40387 (11.8)	50%	189192 (55.4)	45%	229579 (67.3)	47%

theory, both of the goals--25% energy savings by 1993 and 50% savings by 2000--can be achieved just by improving the U-values of windows, opaque walls, and roofs, according to values of the expected new building codes. In practice, however, improvement of the U-values of the windows also leads to a reduction of the transmitted natural light, and, therefore, it will be necessary either to enlarge the window area or increase the amount of artificial lighting in order to obtain the same level of visual comfort. The energy analyses of increased window area are described in Table 4.

While lighting control will reduce the energy for electrical lighting, it will always increase energy consumption for heating because of the reduced internal loads from the lighting system. Tables 3 and 4 show the influence on the energy balance for three different control strategies (on/off and dimming, no base load). With on/off control, the saving potential for electric lighting is between 22% and 29%, and with dimming control, the saving potential is between 50% and 54% (DK-BC 93 and DK-BC 2000, respectively). When the increase in heating energy consumption is taken into account, the total energy savings are reduced 23% to 27% (DK-BC 93) and 41% to 44% (DK-BC 2000). The energy cost savings are slightly higher.

The main difference between Table 4 and Table 3 is the increased window area (south-facing room) for building codes 1993 and 2000 as a compensation for the reduced light transmission of the glazing.

Figure 5 shows the total energy balance for the three different building codes with 15% window area. The internal heat load from lighting (variable due to lighting control strategies), equipment, and people is fairly low during occupancy, so the energy balances show that heating (radiators and mechanical ventilation) is the largest contributor to the energy balance. The heat transmission for DK-BC 82 through the thermal envelope for the conditions in Table 1 contributes almost 75% of the total heat loss. An analysis shows that for DK-BC 82 between 45% and 50%

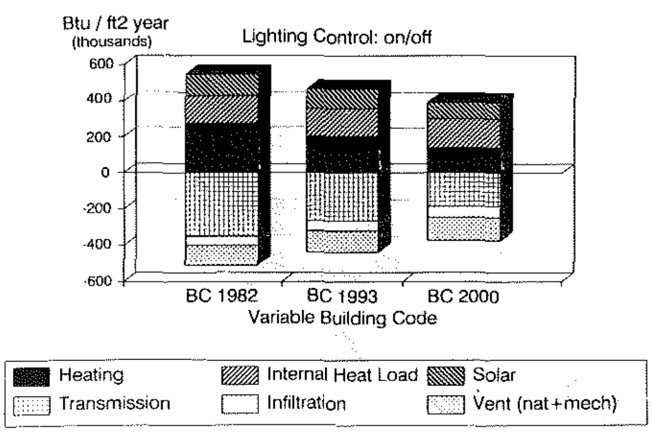

Figure 5 *Yearly energy balance, 15% window area—general building description.*

of the total heat loss (transmission, infiltration, natural and mechanical ventilation) is heat loss through the windows.

During the last couple of years, developments in window and glass technology have improved the U-value, using combinations of gas-filled windows, windows with low-emissivity coatings, and evacuated windows. This indicates that the first step toward low-energy buildings will be the use of improved windows with low U-values.

Calculations show that changing the U-values as described in Table 1 will reduce transmission heat losses in the actual case by 24%.

Because of the reduction of the solar transmission coefficient from 76% to 69%, solar gain is reduced by approximately 8%. Still, the calculation shows that heating consumption according to DK-BC 93 is reduced by approximately 25% compared to DK-BC 82.

For the case of DK-2000, the U-values for the exterior wall are changed to 0.044 Btu/(h·ft^2·°F) (0.25 W/m^2·K) and those for the roof to 0.035 Btu/(h·ft^2·°F) (0.2 W/m^2·K). The U-value for the window is 0.16 Btu/(h·ft^2·°F) (0.9 W/m^2·K) with a solar transmission of 51%. In this case, the calculation shows that the heating consumption is reduced by approximately 48%.

CONCLUSION

The purpose of this study was to examine the possibilities of reducing the energy needs for lighting and heating using light control systems and changing the U-values of windows, opaque walls, and roof areas according to two new building codes as proposed in the Danish energy plan, Energy 2000.

The integrated daylight and energy software system, ADELINE, was used to analyze the indoor climate and energy savings. The experience from the analysis has proved that the integrated system can be used in designing energy-efficient buildings to simulate the complex and dynamic behavior of buildings under realistic conditions of use and operation. The system has given new possibilities for the integration of analysis of natural daylighting, artificial lighting, and lighting control strategies with analysis of energy and thermal performance of buildings including visual and thermal comfort. SUPERLITE calculates the amount of daylighting in buildings. The results are being linked via a link program (SUPERLINK) to the thermal simulation tool TSBI3, which provides accurate calculations for saved energy with different daylight strategies and lighting control systems.

The simulations indicate energy-saving potential for lighting between 22% and 29% by using an on/off lighting control system and up to 54% by using a dimming control system. Also, the results show that in spite of the reduction in the heat gain from the lighting system, a reduction in energy for heating of 18% to 50% can be achieved by improving the building envelope. A total reduction of 50% in the need for energy produced from fossil fuels, as described in the Brundtland Report, "Our Common Future," and in the Danish energyplan, Energy 2000, can therefore be regarded as an ambitious but not unrealistic goal.

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