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Low-energy office buildings using existing technology: simulations with low internal heat gains

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Abstract

Although low-energy and nearly zero-energy residential houses have been built in Sweden in the past decade, there are very few examples of low-energy office buildings. This paper investigates the design features affecting energy use in office buildings and suggests the optimal low-energy design from a Swedish perspective. Dynamic simulations have been carried out with IDA ICE 4 on a typical narrow office building with perimeter cell rooms. The results from the parametric study reveal that the most important design features for energy saving are demand-controlled ventilation as well as limited glazing on the façade. Further energy-saving features are efficient lighting and office equipment which strongly reduce user-related electricity and cooling energy. Together, the simulation results suggest that about 48% energy can be saved compared to a new office building built according to the Swedish building code. Thus, it is possible, using a combination of simple and well-known building technologies and configurations, to have very low energy use in new office buildings. If renewable energy sources, such as solar energy and wind power, are added, there is a potential for the annual energy production to exceed the annual energy consumption and a net zero-energy building can be reached. One aspect of the results concerns user-related electricity, which becomes a major energy post in very low-energy offices and which is rarely regulated in building codes today. This results not only in high electricity use, but also in large internal heat gains and unnecessary high cooling loads given the high latitude and cold climate.

Keywords: office building, low energy, dynamic simulations, cooling, electricity, lighting, building envelope, HVAC, internal heat gains

Background

According to the European Union's Directive on Energy Performance of Buildings, all new buildings within the union must be nearly zero energy by the end of 2020 [1]. The most recent statistics for Sweden show that the total delivered energy to existing office buildings was around 210 kWh/m^2/year in 2005 [2], whereof the first half was electricity and the other half was district heating and cooling. Regarding new office buildings, the energy performance has been improved, in terms of reduced heating loads, but the electricity for lighting and equipment is still high. The high electricity use results in large primary energy demands in general and also in internal heat gains and heat surplus, leading to unnecessary cooling loads given the high latitude and cold climate.

Good examples of low-energy and nearly zero-energy residential houses have been built in Sweden during the past decade [3,4]. However, at the time of writing, there are very few examples of low-energy office buildings. In Germany, on the other hand, a number of passive and low-energy office buildings have been constructed and evaluated (see examples of demonstration projects in [5,6]). Also, research on energy efficiency potential for a passive office building in Germany has been carried out with dynamic simulations by Knissel [7]. Knissel shows that the primary energy requirement of an example building in Frankfurt can be reduced by 70% with high insulation levels in the building envelope, low electricity consumption for equipment and lighting, no active cooling, heat and humidity recovery and earth-to-air heat

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exchangers. These German experiences are clearly important for the development of future zero-energy office buildings. However, they must be adapted to a Swedish context, as building techniques, climate conditions and indoor comfort criteria differ between the countries. For example, the sum of heating and cooling degree days is larger and the amount of useful daylight is smaller in Sweden compared to Germany, which affects the heating, cooling and lighting strategies. In order to bridge this gap, the project 'Energy-efficient office buildings with low internal heat gains: simulations and design guidelines' was initiated. The overall aim of the project is to provide knowledge to the Swedish building industry, supporting the development of cost-effective office buildings with good indoor climate and very low energy use. The main goal is to reduce the annual energy use by 50%, compared to the requirements in the Swedish building code.

This paper describes the second phase of the project, a parametric study carried out with dynamic simulations on a typical office building. The objectives of the study are to:

- Reveal important design features when designing a low-energy office building
- Present an office building with a good indoor climate, which uses less than half the energy compared to a new office building, including user-related electricity.

The obvious advantage with such reduction in energy is that the remaining demand can be met by renewable sources like wind, solar, geothermal or biomass, enabling a net zero-energy office building. The paper discusses recommendations for architects and engineers, regarding the design of future low-energy office buildings. Cost-effectiveness is considered, in a way, by using proven techniques that are available on the market today.

Methods

This section describes the overall method used for the dynamic simulations carried out with the software IDA ICE 4 on a model of a typical narrow office building with perimeter cell rooms. First, a reference building was modelled as a base case, designed to correspond to the energy regulations in the Swedish building code. Then, different design features were studied in a parametric study, and the results were analysed and compared to the base case. The parameters which were analysed were airtightness, insulation levels and thermal mass of the building envelope, glazing and solar control, cooling and ventilation strategies as well as control and installed power of lighting and electric equipment. Finally, the most effective design features were combined as the best case solution and simulated in order to obtain the maximum energy saving potential with a proven technique.

The parametric study did not include the study of different heating and cooling systems. Only the building's actual heating and cooling demand was investigated and district heating and cooling with a coefficient of performance (COP) of 1.0 was assumed.

The simulation software

IDA ICE 4 is a dynamic multi-zone simulation program for the study of indoor climate of individual zones within a building as well as whole-year energy consumption for the entire building. It uses the neutral model format language and hence enables the user to change and write new models. IDA ICE was developed in the mid-1980s at the Royal Institute of Technology (KTH) in Stockholm, Sweden, and now serves a global market. The simulation tool is provided by EQUA Solutions AB (Solna, Sweden), and it has been validated according to CEN 13791, ASHRAE 140–2004, CEN 15255, CEN 15265, CIBSE TM33, RADTEST and Envelope BESTEST [8].

The base case

The virtual reference building is a typical large office building with single office rooms along the façades and a central core with stairways, elevators and other facilities. The building is a six-storey building with a narrow shape (approximately 66 m × 16 m) with the short sides orientated to the east and the west (see Figures 1 and 2) [9]. The room height is 3.2 m and the floor height is 3.5 m with 0.3-m concrete intermediate floors and a thin ceiling. Each floor is 1,030 m^2 with a total heated net floor area of 6,180 m^2. More building data can be seen in Table 1. The base case input was chosen to correspond to the Swedish building code BBR18 [10]. In addition, the input is, to a great extent, in line with the standardized input parameters for energy calculations in office buildings (the SVEBY standard), provided by the Swedish Property Federation [11].

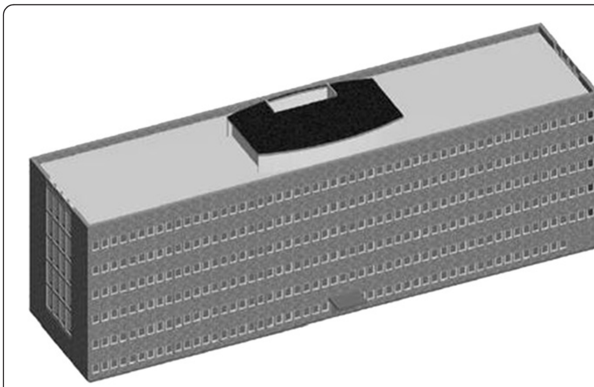

Figure 1 The reference building.

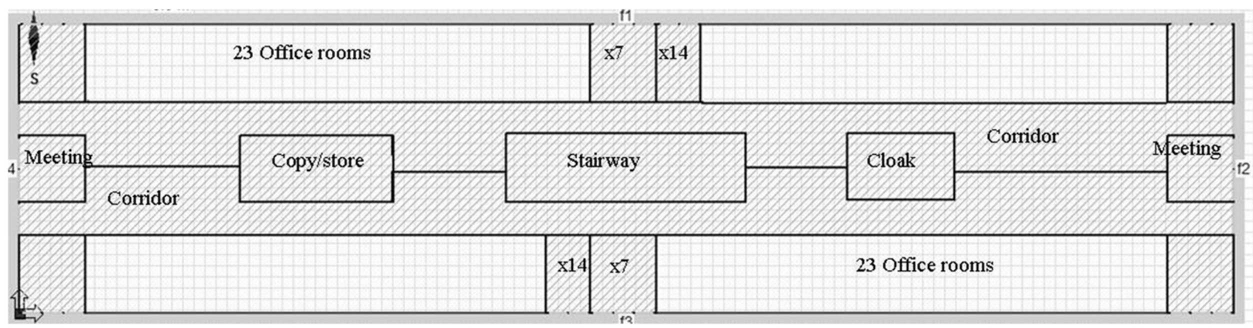

Figure 2 A typical floor plan with thermal zones modelled in IDA ICE.

Results and discussion

This section presents the results and analysis from the parametric study performed on the reference building. Results are displayed as the annual delivered energy for heating, domestic hot water, cooling, fan electricity and other facility electricity as well as user-related electricity for lighting and office equipment. Distribution losses for heating, hot water and cooling are included in the presented results.

The base case

The total delivered energy for the base case is 139 kWh/m^2/year including the user-related electricity for lighting and equipment (see Figure 3). Excluding these, the delivered energy is 92 kWh/m^2/year which is below the requirement in BBR 18 of 100 kWh/m^2/year plus the addition of large airflows. Hence, the base case achieves the regulation with a small margin. The most dominating posts are heating energy (48 kWh/m^2/year) and electricity for lighting and equipment (48 kWh/m^2/year). Even though internal heat gains from lights and equipment are quite large, and the cooling set-point is strict (23°C), the heating load dominates at this high latitude.

Building envelope design

In the first parametric setup, the building envelope was studied. Thermal mass, insulation levels, airtightness, window-to-wall ratio (WWR), orientation and solar shades were varied. The results are presented as total increase or decrease in heating, cooling and electricity, compared to the base case. The results in Figure 4 show that thermal mass has a rather small impact on the heating and cooling demand and that the saving potential for a heavy construction can save 2.5 kWh/m^2/year at most compared to the base case. This result indicates that the cooling load, due to solar gains and internal heat gains, is not large enough in countries at high latitudes to take advantage of thermal mass. Note that the reference building has a quite modest WWR (35%) compared to many modern office buildings, which implies that the solar heat gains are rather small. The result also indicates that there might already be enough thermal mass in the concrete floors alone, despite the ceilings and carpets. The reference building is large with many floors and maybe it cannot benefit from any more thermal mass. Regarding insulation levels and U-values, it is obviously more effective to choose passive house windows ($U = 0.9$ W/m^2°C) than passive house walls ($U = 0.1$ W/m^2°C), despite the rather modest WWR. However, this result depends on the base case starting points, which provided an improvement for the windows from 1.4 to 0.9 W/m^2°C and for the wall elements only from 0.2 to 0.1 W/m^2°C. The negative aspect with improved U-values is the increased cooling demand, but this is compensated by the even larger decrease in heating demand. With a combination of passive house windows and passive house walls, the total energy saving potential is 11 kWh/m^2/year compared to the base case. Finally, an improved airtightness turns out to have a large impact on the building's heating demand. The result is not surprising since the base case has a particularly leaky building envelope (1.6 l/s/m^2 envelope area at 50 Pa). According to the simulation results, the Swedish passive house criterion for airtightness is sharper than the international criterion, at least for the shape of the reference building [12,13].

Figure 5 shows the impact of a larger window area and different solar shading systems. These results indicate that a larger WWR has a significantly negative effect on energy savings, both for the heating and cooling demand. In total, an extra 25 kWh/m^2/year is needed for the case with WWR of 60% compared to the base case with WWR of 35%. Another negative effect with large glazing amounts is the risk of glare. According to a daylight study performed by Dubois and Flodberg [14] on a similar building, the optimal glazing-to-wall ratio (GWR) in Sweden is 20% to 40%, with the lower value preferable on the south façade where the risk of glare is higher. Furthermore, the study shows that increasing the GWR to more than 40% has a negligible effect on available daylight inside the building, and no electric lighting will therefore be saved. Hence, the results presented in

Table 1 Building data and base case input

Parameter		Simulation input	Comment
Climate conditions	Location	Stockholm 59.35°N, 17.95°E	
	Dry-bulb temperature, minimum/mean/maximum	−18.3°C:6.5°C:26.1°C	
	Horizon angle	15°	
Dimensions	Heated floor area (A_{temp})	6,180 m^2	
	Air volume	19,776 m^3	
	Envelope surface	5,193 m^2	
	Surface-to-volume ratio	0.26/m	
	Façade surface	3,133 m^2	
	WWR	35%	GWR 31%
	WFR	18%	
Building elements	External wall *U*-value	0.20 W/m^2°C	170 + 50-mm mineral wool
	External roof *U*-value	0.11 W/m^2°C	300-mm mineral wool
	External floor *U*-value (excluding ground resistance)	0.17 W/m^2°C	200-mm EPS
	Windows *U*-value (including frames)	1.4 W/m^2°C	Pilkington Suncool 2 glass
	Glazing	LT 72%, SHGC 43%	Pilkington Suncool 70/40
	Internal blinds	0.83 × SHGC	SHGC multiplier
	Total UA transmission	2,119 W/°C	
	Thermal bridges	445 W/°C	Calculated with HEAT2
	Air leakage rate	1.6 l/s/m^2 at 50 Pa	Envelope surface
Heating/cooling efficiency	Boiler COP	0.9	Total heat supply
	Heating coil COP	0.9	In air handling unit
	Domestic hot water COP	0.9	
	Domestic hot water use	2.0 kWh/m^2/year	SVEBY standard
	Chiller COP	0.9	Total cooling supply
	Cooling coil COP	0.9	In air handling unit
Thermal climate	Set-points for mean air temperature	22°C to 23°C	Normal target values
Ventilation	Ventilation operating hours	Weekdays, 0700 to 1900 hours	
	Constant air volume	1.5 l/s/m^2	SVEBY standard
	Heat exchanger efficiency	70%	Yearly average
	Total SFP	2.0 kW/(m^3/s)	BBR 18
	Supply air temperature	17°C	
Office operation	Office hours	Weekdays, 0800 to 1800 hours	1-h lunch break
	Occupant space	20 m^2/person	SVEBY standard
	Occupant heat	108 W/person	Sensible and latent heat
	Occupancy factor	0.7	SVEBY standard
Lighting	Installed power in office rooms and other spaces	10 and 6 W/m^2	
	Control	Manual switch on/off	
Computers and office equipment	Power on/standby	140/10 W/person	

WWR, window-to-wall ratio; WFR, window-to-floor ratio; SHGC, solar heat gain coefficient; COP, coefficient of performance; SFP, specific fan power.

this article are supported by Dubois and Flodberg's study, and it can be recommended to keep the glazing amount as small as possible in order to save energy and to avoid glare, but not less than 20% in order to secure enough daylight and view out. The building orientation, on the other hand, does not affect the whole building energy use because of the symmetry and compactness of the building. The study of solar shading devices indicates that the further out in the façade the blinds are placed, the more cooling energy can be saved, but in return, more heating energy will be needed. However, the overall effect is modest. Therefore, climatic conditions and

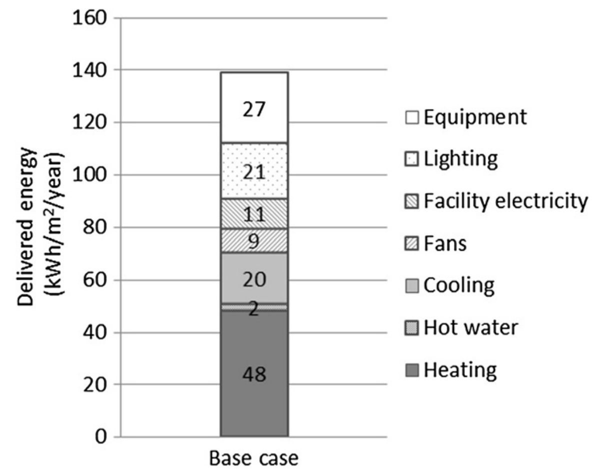

Figure 3 Total delivered energy for the base case.

the number of heating and cooling hours must be considered when selecting a solar shading strategy. It may not be profitable with external blinds if the daytime heating hours exceed the cooling hours or if external blinds are much more expensive due to high wind exposure. One possible, but rather expensive, solution is to have both internal and external solar shades and alternate these in order to optimize the solar heat gains in different seasons. It could also be an alternative to improve the glazing performance and select a glass with a low solar heat gain coefficient. However, there is a risk that the solar heat gains are reduced more than needed, creating an unnecessary heating load, and that the visual transmittance and window view are degraded.

HVAC strategies

Figure 6 shows the results from the study of temperature set-points, heat exchanger efficiencies, specific fan power (SFP), ventilation strategies and user-related electricity. The improvement in heat exchanger efficiency (eta) has a rather small impact on the reduction of heating. Improving the efficiency from 70% to 80% yields a saving of 3 kWh/m^2/year in heating energy, and improving the efficiency from 80% to 85% saves no heat at all. The explanation can be that the largest heating demand in an office occurs during the night when the air handling system is off. During office hours, the building is partly heated by internal gains and solar gains and the heat exchanger is even bypassed at times. The SFP was also improved in the parametric study. The base case fan efficiency, with a SFP of 2.0 kW/(m^3/s), was improved to 1.5 kW/(m^3/s). However, this only decreased the electric energy with 2 kWh/m^2/year. The greatest saving potential occurs when changing the CAV system into a variable air volume flow (VAV) system with airflows depending on indoor temperatures and CO_2 levels. For the reference building, a total of 21 kWh/m^2/year can be saved which is 15% of the total energy use. This result is in line with recommendations from the Passive House Institute, which states that comfort and a good indoor air quality should be ensured and provided by using just the necessary air quantities [15]. Modern Swedish office buildings often have strict indoor temperature targets at about 22°C to 23°C during working hours. The energy saving potential when allowing a larger mean air temperature range, for example 21°C to 24°C, is far from negligible. According to this study, 7 kWh/m^2/year (15%) of heating energy and 5 kWh/m^2/year (24%) of cooling energy can be saved by accepting a larger range in indoor temperatures. To avoid thermal dissatisfaction, it is important to keep the operative temperature close to the mean air temperature by avoiding, for example, solar radiation impinging on the occupants. The figure

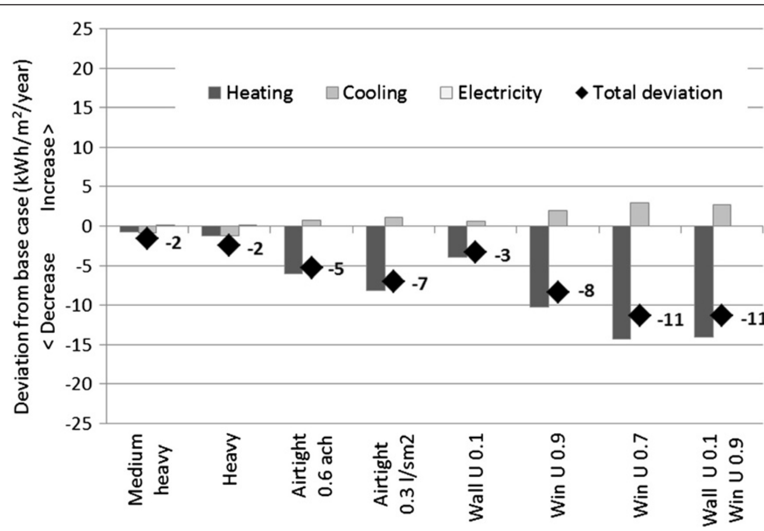

Figure 4 Impact of insulation, thermal inertia and airtightness on total delivered energy.

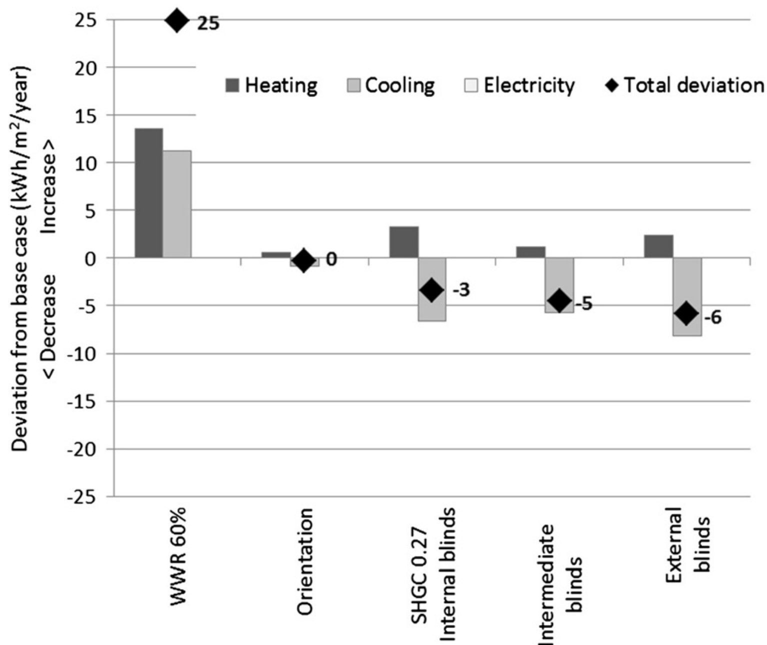

Figure 5 Impact of window area and solar shading systems on total delivered energy.

also shows the potential cooling effect from mechanical night ventilation, with variable airflows at night and heavy constructions. The energy saving potential is negligible (<2 kWh/m^2/year) compared to a similar model without night ventilation. This indicates that cooling with night ventilation might not be profitable in a Nordic country. Cooling with mechanical night ventilation actually saves some fan electricity in the simulation even though the fans operate more hours. This is because during a heat wave, night ventilation reduces the morning temperature; thus, the fans can operate with reduced airflows during the first working hours.

Lighting and electric equipment

The improvement in office equipment and lighting has a large impact on electricity, heating energy and cooling

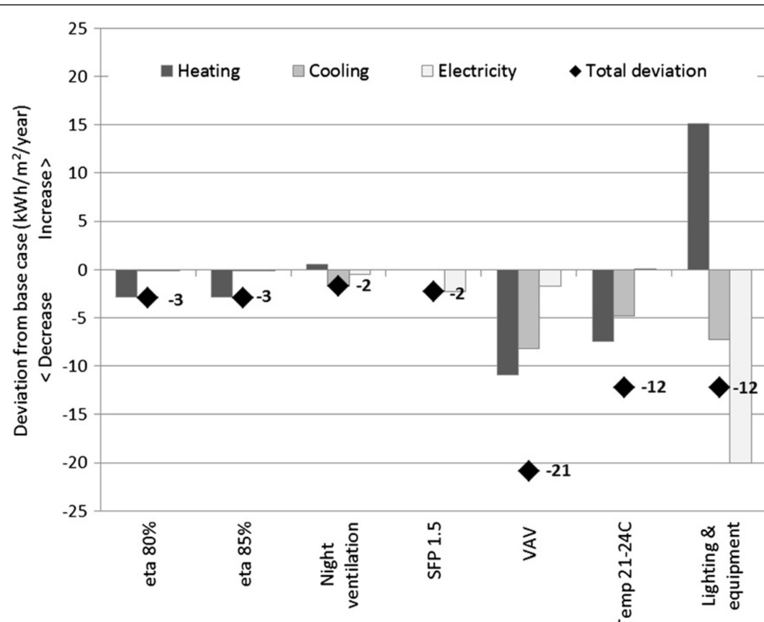

Figure 6 Impact of HVAC strategies and user-related electricity on total delivered energy.

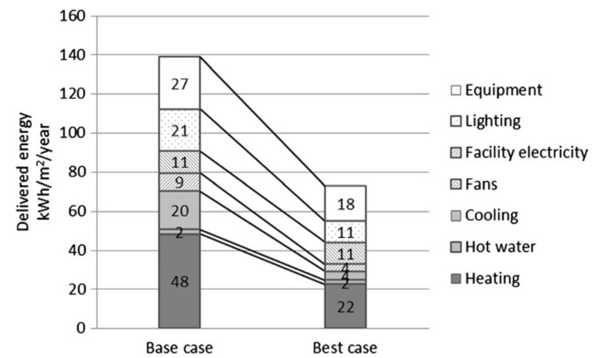

Figure 7 Energy saving potential with the best case solution.

energy, as was shown in Figure 6. When using more efficient office equipment and lighting, with reduced installed powers (EPD 55 W/room, LPD 8 and 4 W/m^2) and improved control (no standby losses at night and lighting with daylight dimming control). Compared to the base case, approximately 10 kWh/m^2/year of electric energy is saved when improving the office equipment and another 10 kWh/m^2/year is saved when improving the lighting system. Meanwhile, the cooling energy decreases and the heating energy increases due to reduced internal heat gains. The total energy saving potential, compared to the base case, is 12 kWh/m^2/year when both office equipment and lighting are improved. This result shows that it is desirable to reduce the internal gains even though the heating load increases. Furthermore, the results show that the available amount of daylight in Sweden is sufficient to reduce the electricity use for lighting to the same level as in Germany [7].

Best case scenario

Figure 7 presents the most efficient design features from the parametric study, combined as the 'best case scenario' with the intention to reach a low-energy solution (see design features in Table 2). By improving walls and windows, reducing window-to-wall ratios, introducing demand-controlled ventilation and lighting, allowing a larger range in temperature and installing more efficient equipment which are completely turned off outside office hours, the heating energy, cooling energy and electricity use can decrease significantly. The best case solution shows a great improvement in especially heating and electricity use. The space heating energy is reduced by 26 kWh/m^2/year (54% heating energy saved and 19% total energy saved). The total electricity use is reduced by 25 kWh/m^2/year (36% electricity saved and 18% total energy saved). The reduction in cooling energy is 15 kWh/m^2/year (77% cooling energy saved and 11% total energy saved). The total saving potential is 66 kWh/m^2/year (48%). This total energy use can probably be further reduced if an effort is made to reduce the remaining facility electricity, in particular energy for pumps which in this study was set to 9 kWh/m^2/year and not analysed further.

Table 2 Input for the best case scenario

Parameter	Simulation input
Airtightness	0.3 l/s/m^2
Wall *U*-value	0.1 W/m^2°C
Window *U*-value	0.9 W/m^2°C
Solar control	External blinds
Heat exchanger efficiency	80%
SFP	1.5 kW/(m^3/s)
Air flow	Variable (VAV)
Tenant electricity	50 W/person; off during the night
Lighting	8 W/m^2; daylight dimming and occupancy switch-off

Thermal conditions for the warmest and coldest days in the best case simulation are displayed in Figures 8 and 9. The mean air temperature is allowed to swing between 21°C and 24°C, and the operative temperature stays close to the mean air temperature, between 20.9°C and 24.3°C, during office hours.

Conclusions

Dynamic simulations were carried out with IDA ICE 4 on a typical narrow office building with peripheral individual rooms in Sweden. The simulations resulted in a very low-energy office building with a total end-use energy of 73 kWh/m^2/year for heating, cooling, facility electricity and user-related electricity. The result shows that 48% energy can be saved compared to a traditional modern office building, which means that the initial aim of this project was reached. If renewable energy sources, such as solar energy, geothermal energy and wind power, are added, there is a potential for the annual energy production to exceed the annual energy consumption and a net zero-energy building can be reached. The study showed that the following design features are essential for achieving this low-energy office building in Sweden:

- Reasonable WWR
- Demand-controlled ventilation
- Demand-controlled lighting and low-power equipment
- Wider temperature set-points
- Well-insulated and airtight building envelope.

These design features are not very expensive solutions, and nowadays, they are rather well mastered. The investment cost is slightly higher compared to the

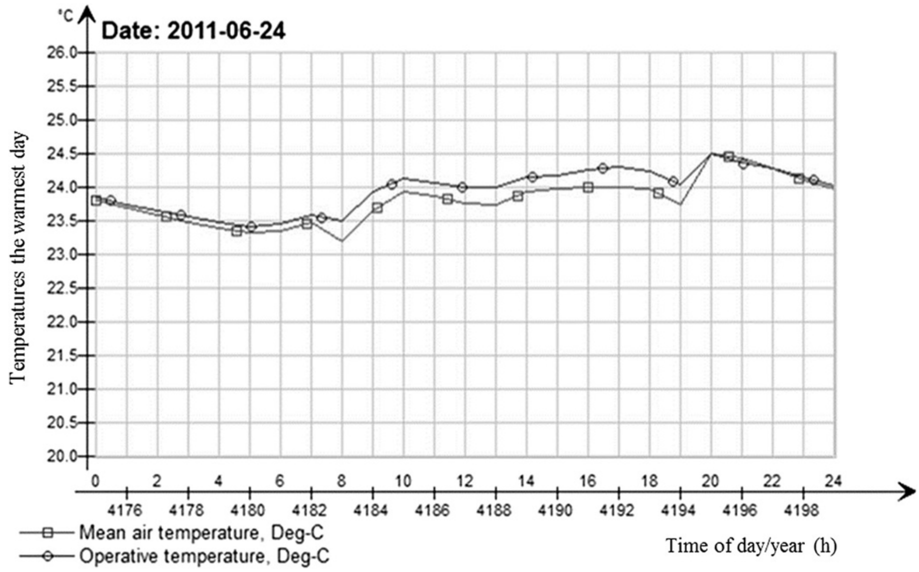

Figure 8 Indoor air temperature and operative temperature for the best case in the warmest day.

base case due to more expensive walls, windows and lighting control systems. The least established of the studied features is photoelectric dimming. Out of all studied design features, reducing user-related electricity is probably the greatest challenge since there has been limited focus on this issue earlier and it is difficult to control the tenant's use of office equipment over time. Power strips and multiple sockets may facilitate the reduction of 'off-mode' losses, but in addition, some kind of incentive is required in order to influence user behaviour. Displaying real-time electricity use is one possible aspect for raising awareness among users.

For low-energy offices, it is crucial to decrease user-related electricity and internal heat gains. A common perception in the building industry is that low-energy buildings would require additional energy when the internal gains are lowered, but this does not apply on office buildings which often include cooling systems. Not only is the user-related electricity diminished, but the cooling energy is also reduced and it will be easier to maintain the desired indoor climate.

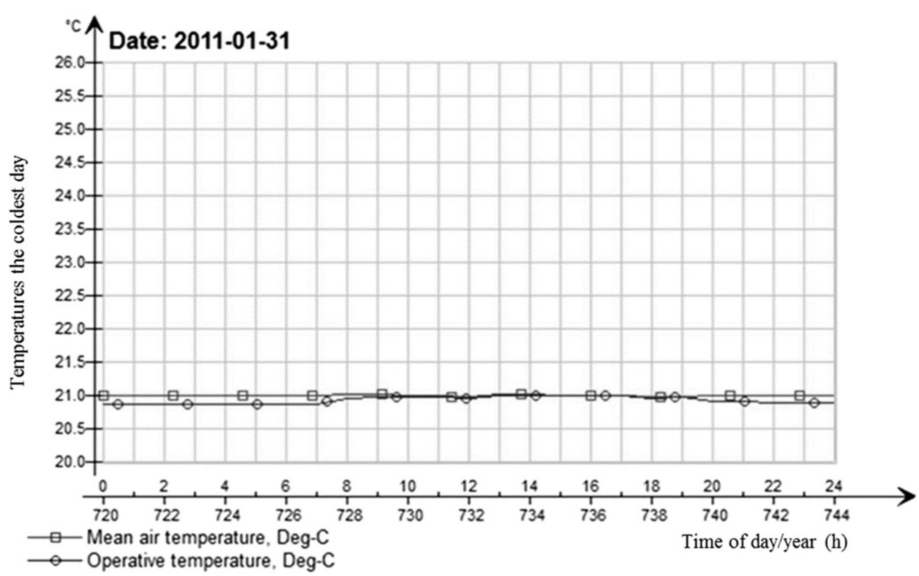

Figure 9 Indoor air temperature and operative temperature for the best case in the coldest day.

Abbreviations
COP: coefficient of performance; GWR: glazing-to-wall ratio; HVAC: heating, ventilation, air conditioning; SFP: specific fan power; SHGC: solar heat gain coefficient; VAV: variable air volume flow; WFR: window-to-floor ratio; WWR: window-to-wall ratio.

Competing interests
This work was supported by CERBOF (Centre for Energy and Resource Efficient Construction and Management of Buildings), SBUF (The Development Fund of the Swedish Construction Industry) and NCC Construction Sweden AB.

Authors' contributions
KF carried out the dynamic energy simulations in IDA ICE. ÅB put together the statistics for electricity use in Swedish office buildings. MCD carried out the daylight simulations with DAYSIM. All authors read and approved the final manuscript.

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