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THE EUROPEAN ENERGY PERFORMANCE OF BUILDINGS DIRECTIVE: COMPARISON OF CALCULATED AND ACTUAL ENERGY USE IN A DANISH OFFICE BUILDING

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ABSTRACT

This paper investigates the actual energy use for building operation with the calculated energy use according to the Danish implementation of the European Energy Performance of Buildings Directive (EPBD). This is important to various stakeholders in the building industry as the calculated energy performance is used for estimating investment security, operating budgets and for policy making. A case study shows that the actual and calculated energy use is practically the same in an average scenario. In the worst-case uncertainty scenario, the actual energy use is 20 % higher than the corrected calculated energy use. More buildings should be investigated in the same manner before any sound conclusion can be made regarding whether the implementation of EPBD in a wide context leads to truly energy-efficient buildings.

INTRODUCTION

The Energy Performance of Buildings Directive (EPBD, 2002) requires that the energy performance of a new building in the European Union be certified to ensure that it fulfills the minimum national requirement. The certification process varies from country to country and is very often based on a calculation of the expected energy use (Lausten et al., 2010). This raises the question: does the calculated energy use correspond to the actual energy use? It is not the first time this concern is put forward, and findings from several investigations show that buildings do not operate as predicted during the design phase (Maile, 2010). There are a number of suggested method which deals with this discrepancy to identify and, if possible, correct imperfect building operation, see e.g. (Reddy, 2006) and the literature review in (Maile, 2010). The issue is also subject to ongoing research (IEA, 2012). The question is, however, relevant to ask again because of the context in which it appears: with the implementation of EPBD, the demand for energy-efficient buildings has become an important piece in a greater puzzle that aims at reducing the overall dependency of fossil fuels. The precision in calculated energy use is thus not only important to building owners and whoever pays the energy bill but for society as a whole. This was initially expressed by the demand for a revision of the national minimum requirement every five years (EPBD, 2002) which was followed up in recast of EPBD in 2010 where it is stated that all new buildings constructed after 2020 should consume "near zero energy" (EPBD, 2010).

The deadline for implementing the first edition of the EPBD into national law and a national calculation method was January 2006. Since then many buildings designed to respect national implementations of EPBD have been constructed and is currently in operation. It is therefore interesting to investigate whether EPBD actually leads to energy-efficient buildings. The objective of this paper is to make a comparison between the calculated energy use according to the Danish national calculation method and the actual energy use of a selected office building. The logged data is equivalent to the amount of data produced in many ordinary office buildings. The comparison is therefore based on both logged data, derived data and assumptions. The results are presented as 1) actually measured values, 2) predicted values according to the Danish national calculation method operationalized in the calculation program Be10 (Aggerholm and Grau, 2008) using its defaults, and 3) values corrected for discrepancies between default and actual values. We then perform a sensitivity analysis on the assumptions, discuss our findings, and provide concluding remarks in relation to whether the outcome of this case study indicates that EPBD leads to more energy-efficient buildings.

CASE STUDY

The chosen case is a 5.147 m^2 office building in Kolding, Denmark, erected in 2008. Figure 1 and 2 are a picture and a plan of the building, respectively. The expected energy use of the building is 50 kWh/m^2 per year. This is approx. 50 % lower than the minimum requirement in the Danish building code from 2006 and corresponds to the then expected minimum requirement in 2015. The thermal indoor environment and the air quality fulfil class I according to (EN 15251, 2007) with a 5 % margin. The expected energy use is calculated according to the Danish national calculation method operationalized in the calculation program Be10 (Aggerholm and Grau, 2008).

The annual actual energy use of the building is only available as the total electricity use and total heating energy for the building as a whole. Total energy use for 2010 is 42.4 kWh(t)/m^2 for district heating and 34.9 kWh(e)/m^2 for electricity. The Danish primary energy factor on district heating is 1.0 and for electricity, it is 2.5, which makes the total 130 kWh/m^2 in primary energy. To compare the actual with the calculated values in Be10, the energy use must, however, be separated into heating energy for hot water and space heating, and electricity for appliances, mechanical ventilation, lighting, mechanical cooling and other installations. This separation is described in the following sections. Furthermore, the calculated energy use is corrected for unforeseen deviations such as differences in weather data and deviations from standard assumptions in Be10.

Heating

As stated earlier, the total energy use for heating in 2010 is 42.4 kWh(t)/m^2. This covers energy for hot water production and space heating which needs to be separated for comparison with the calculated energy use.

The measured tap water use is used for this purpose. The tap water use (hot and cold) on the office floors is 108 l/m^2 per year. It is assumed that 30 l/m^2 per year of this consumption is hot water. The assumption is based on the detailed measurement of the hot water use in four office buildings (Bøhm et al., 2009). There is furthermore a tap water use of 129 l/m^2 per year for the bathing facilities in the basement. Assuming an average bathing temperature of 38 ºC, 88 l/m^2 per year is hot water at 55 ºC and the rest is cold water at 10 ºC. The actual total hot tap water use is thereby estimated to be 117 l/m^2 per year. For comparison, the standard assumption in Be10 is 100. A hot tap water use of 117 l/m^2 per year corresponds in Be10 to an energy use of 6.1 kWh(t)/m^2 year. Be10 also operates with heat loss from hot tap water supply system. The actual loss is assumed to correspond to the calculated heat loss of 3.2 kWh(t)/m^2 year.

The actual energy use for space heating is the total heating use minus the use for hot tap water, ie. 33.1 kWh(t)/m^2 per year. The calculated energy use is 19.0 kWh(t)/m^2 per year of which 1.2 kWh(t)/m^2 per year is heat loss from the heating supply system. Thus, the actual energy use for heating is immediately 43 % higher than the calculated. The calculated energy use must, however, be corrected before the two consumption are comparable:

- *Thermal indoor environment class I*

  The standard assumption for heating set point in Be10 is 20 ºC corresponding to class II. The heating set point in class I is, however, 21 ºC. Using 21 ºC as heating setpoint in Be10 increases the energy use for space heating to 21.9 kWh(t)/m^2 per year.

- *Actual weather data*

  There will obviously be a difference in the weather data used in Be10, the Danish design reference year DRY (Jensen and Lund, 1995), and the actual weather conditions for a given year. To correct for this difference, one must compare solar and wind corrected degree-days for DRY with the current year at the current location. However, only shadow degree days (ie. without solar and wind correction) is available for the current year and location. Shadow degree days for DRY is 2953 K·h, and the corresponding degree days for 2010 close to the current location is, 3854 K·h (EMD, 2011). The shadow degree hour for 2010 is thus 31 % higher than for DRY, and calculated energy use for space heating corrected for this difference becomes 28.6 kWh(t)/m^2 per year.

The calculated energy use for space heating corrected for a higher heating set point and differences in the weather data is thus 14 % lower than the actual energy use. It is noted that the assumptions made in the adjustment of the calculated energy for heating is subject to some uncertainties. These are discussed later in this paper.

Electricity

As stated earlier, the total electricity use in 2010 is 34.9 kWh(e)/m^2. This includes electricity for the appliances (computers, printers, etc.), ventilation fans, lighting (indoor and outdoor), mechanical cooling and other building operation services (e.g. water pumps). As mentioned earlier, the total electrical energy use must be divided into these sub-items to compare the actual energy use with the energy use calculated with Be10. There are secondary meters installed on almost all of the above-mentioned sub-items but none of them are being logged. However, some system data is available that can be used to extract some of the sub-items from the total electricity consumption. Other extractions must rely on assumptions.

According to EPBD, only energy for building operation should be included in the assessment of building energy performance. Electricity for appliances is therefore separated from electricity for building operation. The total electricity use is on average 79 % of total primary energy use in a new office building in Denmark (Marsh et al., 2008). Approximately 67 % of this is used for appliances. For lack of better, this is assumed to be the case for the current building. This leave 11.5 kWh(e)/m^2 for building operation. This electricity use is divided into the sub-items as follows:

- *Mechanical ventilation*

  The building has two variable air volume ventilation systems. The measured specific fan power (SFP) for both systems was 1.45 kJ/m^3 at maximum airflow. The average yearly SFP in Be10 was initially estimated to be 25% lower, i.e. 1.16 kJ/m^3, resulting in a calculated energy use of 4.5 kWh(e)/m^2 year incl. night ventilation. The building management system (BMS) logged the hourly fan power consumption for both systems throughout 2010. The resulting average SFP is 1.3 kJ/m^3. Both systems were for unknown reasons in operation from 5 am every weekday. The default operation time in Be10 is from 8 am to 5 pm. The calculated energy use is 5.7 kWh(e)/m^2 when corrected for this early start-up. The total actual energy use for ventilation is 6.3 kWh(e)/m^2 which is derived from the logged hourly fan power. The actual energy use for ventilation is thus 10 % higher than the corrected calculated energy use.

The air leakage of the building is not considered a significant source of error since it was measured during the construction phase and subsequently used for the calculated energy use. However, it is worth noticing that one of the ventilation system unintentionally was in operation 24/7 in November and December. This operational discrepancy is also contributing to the divergence of the space heating demand.

- *Mechanical cooling*

  Be10 shows no need for mechanical cooling. A more detailed thermal simulation in the design phase, however, identified a cooling need in south-facing zones, which is why the ventilation systems are equipped with a cooling coil. There are no secondary meters on the cooling coils and the BMS has not logged any data in relation to the coils. Instead, the actual electricity use for cooling is derived from an analysis of the hourly data of the total electricity use. Figure 3 shows a number of peaks in the actual energy use in the summer months. It is fair to assume that these peaks are due to an active cooling coil. Isolating these peaks (values above 50 kW) gives an estimated electricity use of 0.8 kWh(e)/m^2 per year for mechanical cooling.

- *Other building operation services*

  Be10 also operates with electricity use for pumps in the heating and hot tap water distribution system. In this case it is assumed that the actual energy use corresponds to the calculated use of 0.2 kWh(e)/m^2 per year.

- *Electrical lighting*

  The only electricity use which remains to be accounted for is lighting. Be10 calculates a electricity use of 4.6 kWh(e)/m^2 per year. Since all other sub-items in the actual energy use has been accounted for, it is assumed that the actual electricity use for lighting is the total actual electricity use for building operation minus electricity for ventilation, cooling and other services, i.e. 4.2 kWh(e)/m^2 per year. This is 10 % lower than the calculated energy use.

An overview of actual, calculated and corrected energy uses are given in Figure 4.

SENSITIVITY ANALYSIS

The total actual energy use is 7 % higher than the calculated energy use from Be10 corrected for weather and behavioural factors, see Figure 4. However, the overall result as well as the differences on the individual sub-items relies on assumptions. The uncertainties in these assumptions are analysed in the following. The uncertainties are summed and illustrated in Figure 4 with error bars.

Heating

One uncertainty is the effect of hot tap water on space heating. A sensitivity analysis shows that if the original assumption regarding the fraction of actual hot tap water is increased by 50 %, then the difference between actual and corrected energy use for space heating becomes 5 %, and if the fraction decreases by 50 % then the difference becomes 27 %.

Another uncertain assumption is the recording of weather data, which was not done locally but at a regional weather station. The corrected calculated energy use for space heating is 0.4 % lower than actual energy use if the number of shadow degree days is 20 % higher, and 37 % lower if the fraction is 20 % lower.

Other calculation uncertainties that may affect the comparison of heating consumptions are differences in theoretical and actual values of thermal conductivity of constructions, energy balance of window and average heat recovery. Furthermore, there may be building dynamics and user behaviour that are not accounted for due to the quasi-steady-state method in Be10.

Appliances

The assumption regarding the fraction of total electrical energy that is used for appliances (67 %) is not only uncertain but also the most crucial assumption in relation to the result of the overall comparison. A sensitivity analysis shows that if the fraction is 57 % (-10 % points), then the total actual energy use for building operation is 21 % above the total corrected calculated use. If the fraction is 77 % (+10 % points), then the total actual energy use for building operation is 6 % below the total corrected calculated use. However, the energy for lighting then becomes unrealistically small (0.7 kWh(e)/m^2). Thus, an average electrical energy use of 67 % for appliances in an office building from literature is considered a relatively good estimate for this low-energy building.

Ventilation

The actual energy use for ventilation was directly derived from logged data in the BMS. The major source of error in the comparison of actual and calculated energy use for ventilation is the fact that one of the ventilation systems unintentionally was in operation 24/7 in November and December. Moreover, it is not possible to assess differences in air flows as Be10 operates with monthly average values.

Mechanical cooling

The calculated energy use based on the one-zonal quasi-steady-state method in Be10 does not indicate a need for mechanical cooling. An hourly-based dynamic calculation, however, identifies a need for cooling. This suggests that the algorithm of Be10 is insufficient in terms of calculating cooling demands.

Other building services

These consumptions are, all things being equal, minor compared to the other sub-items. A sensitivity analysis shows only marginal changes in the total energy use.

Lighting

The actual electrical use for lighting is considered to be what remains when the energy use from all other sub-items are subtracted from the total actual electricity use for building operation. This approach makes the extraction of actual energy use for lighting heavily dependent on the assumed fraction of total electrical energy used for appliances.

Since the lighting system in the building is equipped with motion sensors and daylight control, deviations between actual and calculated energy use for lighting may occur due to differences in assumptions regarding user behaviour and differences between design weather data and actual weather conditions for a given year.

Worst-case uncertainty scenario

Summing up the above-mentioned uncertainties gives a worst-case uncertainty scenario. In this case, the difference between total actual and corrected calculated energy use for building operation is 20 %.

DISCUSSION

The immediate difference between total actual and calculated energy use before correction is 29 %. The primary reason for this is 1) that the year 2010 was an unusually cold year in Denmark (13 % colder than the average), 2) Be10 does not identify a need for mechanical cooling (10 % of the energy use), and 3) deviations between assumed and actual operation of the ventilation system. The most influential assumption is, however, the fraction of total electrical energy used for appliances.

It is noted that the validity of this investigation could have been improved if the analysis was repeated using a different (new) set of measured data. However, we still dare to ask the question: What is needed for better alignment between calculated and actual energy use? First of all, one could set up secondary meters and log data on all sub-items which are included in a Be10 calculations. Furthermore, hourly values of outdoor temperature and solar radiation should be logged close to or on the building. In relation to cooling need, a better algorithm for is needed. Cooling need is difficult to calculate in Be10 as the program operates with only one thermal zone. Furthermore, it is in general difficult to calculate an accurate cooling need, especially in buildings with small absolute energy need (Kalema and Pylsy, 2008) like the one in this case. However, according to the developers of Be10, the cooling algorithm has been improved since the calculation of the featured building. Another issue is the coupling of daylight and artificial lighting, which in Be10 in some cases is inadequate (Petersen, 2008).

In Be10 the building is currently modelled as one thermal zone, and its algorithm is based on a monthly quasi-steady-state method (EN/ISO 13790, 2008). The issues regarding cooling and lighting prediction indicates that multizone modelling may be necessary. A shift from the quasi-steady-state method to a more dynamic method might also be necessary for better prediction. Both, however, adds complexity to the modelling process. Finally, the standard guideline for Be10 (Aggerholm and Grau, 2008) states that internal loads at night should be assumed to be zero. The actual electrical use in Figure 3 shows that the featured building has an electrical standby consumption of approx. 2 W/m^2 during the night. This guideline is therefore critical, as electricity during the night will affect the energy balance of the building.

CONCLUSION

This paper compares the actual energy use of an office building with the energy use calculated with the Danish national calculation method, which respects EPBD. Based on scarce logged data and assumptions, it is demonstrated 1) how to extract the total actual energy use for heating and the total actual energy use for electricity into the same sub-items used in the Danish national calculation method, and 2) how to correct the calculated energy use for deviations in weather data and some user behaviour issues. This enables the comparison of an actual energy use and the calculated use for a certain year.

The results and analysis of a test case shows that the energy use calculated with the Danish national calculation method is 7 % higher than the actual energy use – provided certain assumptions and corrected for unforeseen circumstances such as deviations in weather. In the worst-case uncertainty scenario, the actual energy use for building operation is 20 % higher than the corrected calculated energy use. However, issues in the calculation procedure should be treated and more buildings should be investigated in the same manner before any sound conclusion can be made regarding the effect of the EPBD implementation towards more energy-efficient buildings.

NOMENCLATURE

$kWh(t)$, thermal energy use
$kWh(e)$, electrical energy use

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Figure 1 A picture of Company House III in Kolding, Denmark.

Figure 2 Plan drawings for Company House III in Kolding, Denmark. The colours indicate the various areas for lease and the white areas are common, shared facilities like arrivals area, canteen and meeting rooms.

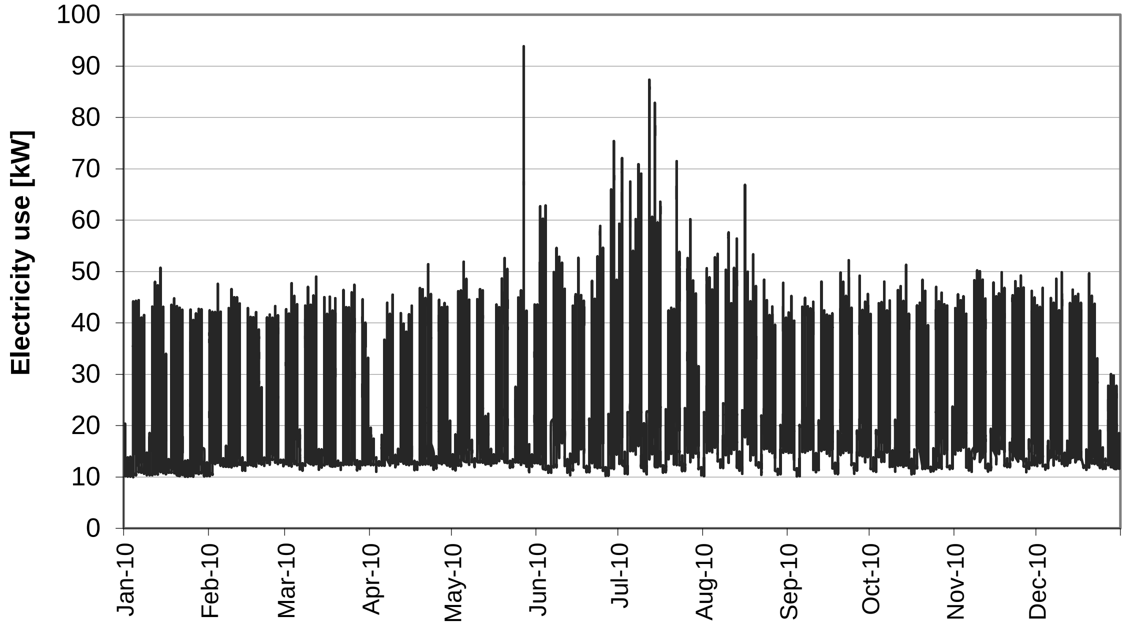

Figure 3 A plot of the total hourly electricity use for both appliances and building operation in 2010.

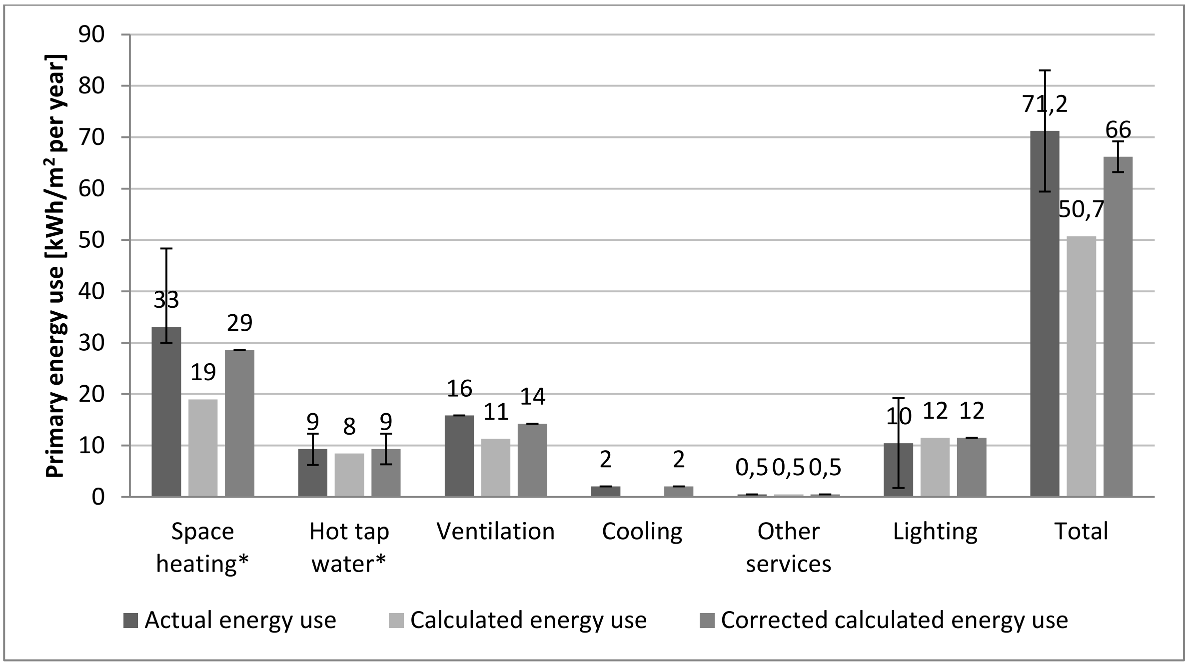

*Figure 4 Actual, calculated and corrected calculated energy use in primary energy. Primary energy factor for electrical energy is 2.5. *incl. heat loss from supply systems*