Sensitivity analysis of the energy demand of existing buildings based on the Danish Building and Dwelling Register

Nielsen, Anker; Wittchen, Kim Bjarne; Bertelsen, Niels Haldor

Published in:
NSB 2014: 10th Nordic Symposium on Building Physics 15-19 June 2014 Lund, Sweden

Publication date:
2014

Document Version
Publisher's PDF, also known as Version of record

Sensitivity analysis of the energy demand of existing buildings based on the Danish Building and Dwelling Register

Anker Nielsen, professor [1]
Kim B. Wittchen, senior researcher [1]
Niels H. Bertelsen, senior researcher[1]

[1] Danish Building Research Institute, Aalborg University, Denmark

KEYWORDS: *Energy demand; Danish Building Regulations; Calculation method; Uncertainty; Energy ratings*

SUMMARY:
The EU Directive on the Energy Performance of Buildings requires that energy certification of buildings should be implemented in Denmark so that houses that are sold or let should have an energy performance certificate. The result is that only a small part of existing houses has an energy performance certificate. The Danish Building Research Institute has described a method that can be applied for estimating the energy demand of dwellings. This is based on the information in the Danish Building and Dwelling Register and requirements in the Danish Building Regulations from the year of construction of the house. The result is an estimate of the energy demand of each building with a variation. This makes it possible to make an automatic classification of all buildings. The paper discusses the uncertainties and makes a sensitivity analysis to find the important parameters. The variations are compared with measured energy demand. The method can be applied in other countries with modifications for local building requirements, climate and building registers.

1. Introduction

In Denmark, energy performance certification has been in use since 1997 with energy performance rating and for new houses (since 2006), including sold or let buildings. The energy rating classifies the building on an efficiency scale ranging from A (high energy efficiency) to G (poor efficiency) (EPBD 2011). The rating is important when buying and selling houses. The problem is that many houses still do not have an energy rating, and that it will take many years to cover the entire building stock. Until ultimo 2013, only 22% of single-family houses had an energy rating. Energy ratings are given in connection with a visit by an energy expert and the result is a rating and a description of possible energy-saving measures. For houses that have not been energy rated, we do not know the energy demand and potential energy savings. An automatic calculation of the energy rating would thus be very useful. It is possible that some owners would make energy saving measures, if they were informed about the energy rating of their property. It would also make it possible for authorities to give an economic subsidy or tax deduction for the buildings with the poorest energy efficiency. The result should be more energy saved for the same money.

It is possible to apply a normal certification method based on monthly values and details on heating system and constructions to make energy demand calculations of existing houses. The problem is that we have to visit the houses and we will not always be able to obtain information about the constructions at the site or in drawings. Another important point is that this would be a very time-consuming and expensive method. The Danish Energy Performance Certification Scheme for existing buildings includes energy demand calculations based on a monthly calculation method (Aggerholm and Grau 2005). This can be used at the visit as you can find some information and have additional information from a guideline with typical constructions. The cost of this is paid by the owner before selling the building. As it will take many years before all buildings have been officially rated, the Danish Building Research Institute (SBi) has described a method (Bertelsen et al. 2011) that can be used without physically visiting the house but only based on available information.

2. BBR data

The Danish Building and Dwelling Register (BBR) has information that can form the basis for the calculation. This has to be supplemented with information from the Danish Building Regulations from the year of construction and some estimates from previous research and information collection (Wittchen 2009 and 2012) by SBi. The following data from BBR are used: building (building type), year of construction, useful floor area in m^2, number of storeys, building footprint in m^2,useful attic area in m^2, basement area in m^2 and external wall material.

The described method can be used for dwellings like single-family houses and blocks of flats. In the following, we only describe the use for single-family houses. The construction year is used to find the actual energy requirements in the Danish Building Regulations. In Denmark, we can expect that these requirements for thermal insulation are respected. We know that many buildings have better insulation or improved windows and we take that into account in the method.

The useful floor area is used for calculating the amount of heat from persons, light, equipment and solar radiation. The number of storeys, the building footprint, useful attic area, and basement area are used in the calculation of the geometry of the building. The external wall material defines the U-value level in the Danish Buildings Regulations.

3. Geometric model

BBR contains no information on building height, length or width. So we have to make an estimate of the geometry. The simplest form is a box-shaped building. We know the roof and floor area as it equals the building footprint. For buildings without attic and basement, we use a box-shaped building. We need the building width. Based on typical Danish buildings, we estimate the building width to be 9 m for single-family houses. The building length is the building footprint divided by the width. Calculations with other length/width proportions show that it does not influence the surface area very much. The storey height is assumed to be 2.8 m as a typical value. The volume and the external wall area can then be calculated.

If the building has a useful attic area, we get an extra wall area based on the attic which is also a box. The box is placed on top of the building box and does not change the floor or roof area. The length of the attic is estimated to be the length of the building. The width and volume of the attic and wall area can now be calculated.

For houses with a basement, this is calculated as a box placed under the building. As it is placed underneath the building, there is no change in floor or roof area. The walls of the box give the basement wall area. Note: We calculate as if the whole basement area is heated, as most people use it like that. The length of the basement is estimated to be equal to the length of the building. The width and volume of the basement and the basement wall area can now be calculated.

3.1 Areas used in the energy calculations

The roof area and the floor area are both equal to the building footprint. The external wall area is the sum of the wall areas of the building box and the attic box. The volume of the building is the sum of the volume of the three boxes. This is a simplification as some part of the volume might be unheated, e.g. staircases.

Another important information is the area of the windows of the building, as windows have a greater heat loss than the rest of the wall area. There is no information on window area or number of glass panes in BBR, so we need to estimate the values. The window area also includes door areas. It is estimated that before 1999 most buildings had a window area covering 15% of the façade area. After 1999, the windows covered 22% based on Wittchen 2009 and 2012. The basement wall has no windows. If we have an attic, then we estimate a window area covering 10% of the attic wall area.

Now we can calculate the window area for the building based on the construction year and possible presence of an attic. The wall area excluding windows is then easy to find.

4. U-value model

U-values for the different building parts are taken from the Danish Building Regulations in force when the building was constructed. Energy requirements were changed in 1961, 1967, 1972, 1977, 1982, 1985, 1995, 1998 and 2008. The five U-values used in the calculation are outer wall, basement wall, floor, roof and window. We do not take into account that we can have different outer wall constructions in the same house.

TABLE 1. Typical U-values and requirements in different periods

Heavy outer wall (> 100 kg/m^2)		Roofs		Windows	
Before 1930	1.2 W/m^{2}K	Before 1950	0.97 W/m^{2}K	Before 1930	3.7 W/m^{2}K
1931-1950	1.5 W/m^{2}K	1951-1960	0.6 W/m^{2}K	1931-1994	2.9 W/m^{2}K
1951-1960	1.5 W/m^{2}K	1961-1976	0.4 W/m^{2}K	1995-2007	1.8 W/m^{2}K
1961-1971	1.1 W/m^{2}K	1977-1994	0.2 W/m^{2}K	From 2008	1.5 W/m^{2}K
1972-1976	1.0 W/m^{2}K	From 1995	0.15 W/m^{2}K	Note: We assume that most old windows are upgraded.	
1977-1994	0.4 W/m^{2}K				
1995-2007	0.3 W/m^{2}K				
From 2008	0.2 W/m^{2}K				

BBR information on the exterior wall material is used to decide whether it is a light or heavy wall as the Danish Building Regulations define different U-values for these wall types. Data about older houses are supplemented by the experience of SBi. Table 1 is an example of the U-value variation over the years for heavy outer walls, roofs and windows. Data for other construction types and periods are given in a Danish report (Bertelsen et al. 2011).

5. Model for energy balance

The total transmission heat loss is found by multiplying the areas with the U-values from the construction year and making a summation of all constructions in the house. For floor and basement walls, we reduced the heat loss by 30% because of the ground.

The volume of the building is needed for calculation of the ventilation loss. As mentioned, the volume also includes internal construction and unheated areas such as staircases and basement. The ventilation is estimated based on SBi's experience gained from other projects. Here it was found that before 1961the air change rate (1/h) was 0.45, from 1961 to 1978 it was 0.4 and after 1978 it was 0.35.

Calculation of heat from sun, persons, and equipment can be complicated. It is theoretically possible to calculate the solar radiation through windows, but there are uncertainties in both the areas and orientation of the windows. The heat from persons, light, equipment etc. is also very uncertain. Another problem is that only part of this heat will reduce the heating energy demand of the building. The solution is to use a value for the useful part of the internal loads from SBi. The useful internal heat gain is estimated to be 55 kWh/m^{2}year, where the sun accounts for half the amount.

To calculate the energy loss, it is necessary to know the indoor and outdoor temperature. The indoor temperature is fixed at 20 °C. We use degree days. In Denmark the degree-day number for the energy calculation is 3600. The useful internal heat gain is calculated for the living area (given in BBR), and does not include for instance basement areas not accepted for living. The energy demand for heating the building in kWh/year (EX) can then be calculated as the sum of the heating and ventilation losses minus the useful internal heat gain.

6. Uncertainty of the parameters

The calculated energy demand is the best estimate based on the information in BBR and the estimates made by SBi based on the knowledge of the Danish building stock. Table 2 lists all the uncertainty parameters.

TABLE 2. List of uncertain parameters

Geometry	U-values	Energy calculation
Width Length Storey height Volume Attic area and width Basement area and width Window area	Walls Roof Floors Window type, number of glass panes translucent area, glass coating, orientation	Ventilation rate Airtightness Useful heat (solar, persons, light and equipment) Degree-hour number Renovation

The method ignores complex geometric buildings like U or L shaped ones. The uncertainty of the U-values is large for buildings constructed before the first nationwide Danish Building Regulation in 1961 – after that time the uncertainty is lower as buildings are normally built in compliance with the Danish Building Regulations. There is no information in BBR as to whether extra insulation has been added after the construction year. In practice, we can expect that energy-saving measures have been implemented in many older buildings.

7. Variations of the result

Measurements of the energy demand of buildings show large variations for individual buildings in spite of their being uniform in construction (Petersen 1997). This is caused by the influence from the users and variations in workmanship etc. This calculation method is based on the variations in the building and only partly takes into account the variation caused by the users and their use of the building. If that variation was fully included, the variation would increase.

An estimation of the uncertainty of the calculations depends on the construction year. Old houses have a large variation and new houses a lower variation. The method provides an upper limit and a lower limit, as given in Table 3. The variation is not symmetric. These limits are in reality upper and lower quartiles as we estimate that 25% of houses have an energy demand higher than the upper limit and 25% of houses have an energy demand lower than the lower limit

TABLE 3. Variations in upper and lower limits during different periods

Upper limit	Lower limit
Before 1961: EX * 1.25 (it is 25% above the average) 1961-1971: EX * 1.15 From 1972: EX * 1.10	Before 1931: EX * 0.60 (it is 40% below the average) 1931-1961: EX * 0.70 1962-1977: EX * 0.80 1978-1995: EX * 0.85 After 1995: EX * 0.90

The lower limit has more variations than the upper limit which is explained by the fact that many old houses have been retrofitted with extra insulation and new windows. The result is an energy demand that is well below the average calculated value (EX). The values in kWh/year are calculated as energy demand per m^2 as this is the basis for the Danish Energy Performance Certification Scheme.

8. Automatic energy rating

The described method to perform automatic energy demand calculations can be used for automatic energy certification and rating of houses that do not have an official energy performance certificate. The auto-rating method can be described as follows:

Using the average energy demand per m^2 (EX) as a basis for automatic rating results in a number of houses would get a better rating than if they had been visited by an energy expert. This problem is solved by calculating the energy demand from the upper-limit energy demand (worst case). Use of this value makes nearly all houses obtain a better rating when an official certification is made later.

The method has been used in a case study of a street with 56 single-family houses. Figure 1 shows variations in energy demand, based on the construction year. It is seen that most houses are built from 1940 to 1960. Most houses with an automatic rating are rated either F or G, the two lowest ratings.

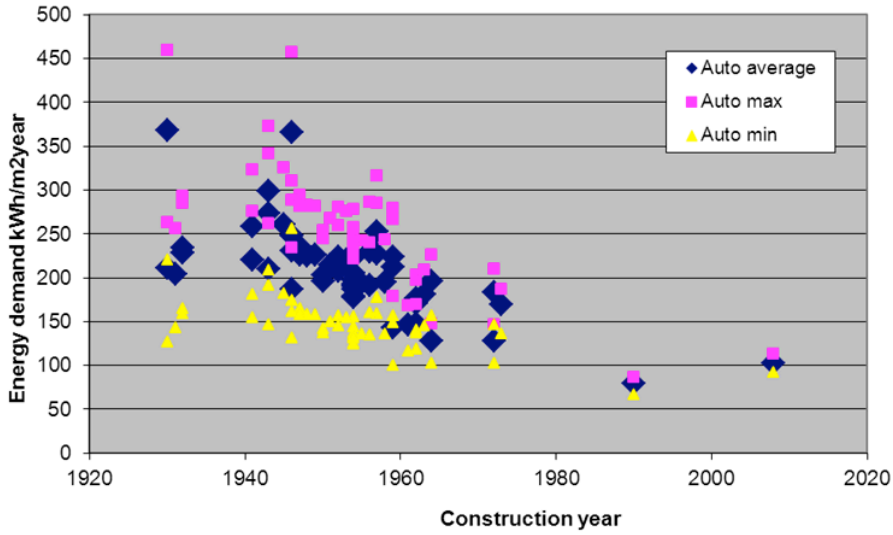

FIG 1. Calculated energy demand of 56 single-family houses versus construction year.

If we compare the official energy rating for the five houses that have an official energy certificate with the result of the automatic rating method based on BBR it is seen that the officially calculated energy demand by the energy expert lies between the upper and lower limits of the automatic method. As expected, the value is closer to the lower limit, as some energy-saving measures were made. These are typically additional insulation, tightening and retrofitting of windows and new heating system.

9. Sensitivity analysis for automatic calculation

A sensitivity analysis is done on a house from 1964 with a Monte Carlo simulation using random values to recreate the variation of the parameters. The calculation data is described in Table 4.

TABLE 4. Case of a single-family house with average values and variations

Geometry • Building footprint 100 m^2 (variations from 95 to 105 m^2) • Storey height 2.8 m (variations from 2.4 to 3.0 m) • Length of house (area fixed – variation in length/width) • Areas of windows 15% (variation from 10 to 25%) • Insulations and constructions in W/m^2K. It is taken into account that there is a possible later insulation of the constructions. • Walls 1964 1.1 W/m^2K (variation from 0.6 to 1.3 W/m^2K) • Windows 1964 2.9 W/m2K (variation from 1.6 to 3.0 W/m^2K) • Roof 1964 0.4 W/m^2K (variation from 0.25 to 0.5 W/m2K) • Floor 1964 0.4 W/m^2K (variation from 0.3 to 0.5 W/m2K)
Other parameters • Air change rate 0.4 1/h (variation from 0.2 to 0.6 1/h) • Indoor climate – constant standard value • Outdoor climate – constant standard value • Heat from persons, equipment and solar radiation – constant standard value

The calculation of 10000 cases gives an average value and a variation for the building:

- Average energy demand 192 kWh/m^2
- In 10% of the cases, the demand is less than 157 kWh/m^2
- In 10% of the cases, the demand is higher than 226 kWh/m^2
- So 80% of all values ranged between 157 and 226 kWh/m^2

This variation is similar to the variation found in other research on buildings' from around 1965. The calculation makes it possible to evaluate the sensitivity of the parameters in the calculation. Table 5 show which parameters have the most influence on the final result.

TABLE 5. The calculated variance for the 9 parameters in the sensitivity analysis

Parameter	Variance	Sum of Variance
Wall U-value	36%	36%
Storey height	19%	55%
Air change rate	15%	70%
Window area	10%	80%
Roof U-value	7%	87%
Windows U-value	6%	93%
Building footprint	4%	97%
Floor U-value	2%	100%
Length/width proportion	0%	100%

The most important parameter is the U-value of the wall, and after that the storey height, air change rate and window area and hereafter the rest of the U-values and the built area. If we do a more correct calculation, we need more information. From this analysis, we see that if we can get better information on the U-values of the wall, the storey height and window area, we reduce the variance in the energy demand calculation as they account for 65% of the variation. The air change rate is very difficult to know without making measurement and it will change during the year – so it is not realistic to get better information on the air exchange rate. For the other three parameters, it is possible to ask the owner about the values and whether extra insulation has been added. It is interesting to note that an improvement of information for a number of the parameters does not have much effect on reducing the variance.

If we use the method to calculate the total energy demand for a group of houses, the estimate will be much better, if we assume that the houses have random variations. For instance we can estimate a single house with a variation of 56%, but for a group of 10 houses is it 18% and for more than 50 houses is it 8%.

10. Measured energy use

Is the assumption realistic if we compare with measured energy consumption in buildings? Figure 2 shows measured energy consumption for houses in relation to construction year (Jensen 2004). The red line is the level of the rules in the Danish Building Regulations from 1961 and onwards. It is seen that for most houses from 1960 to 1996, the energy consumption is below the requirement level. So our assumption that houses follow the rules is realistic and also that many has been improved. After 1996, more houses have a higher energy use than the Danish Building Regulations, probably because a slightly higher indoor temperature will only give a small increase in the energy bill. For older houses, this effect of the indoor temperature variation is blurred.

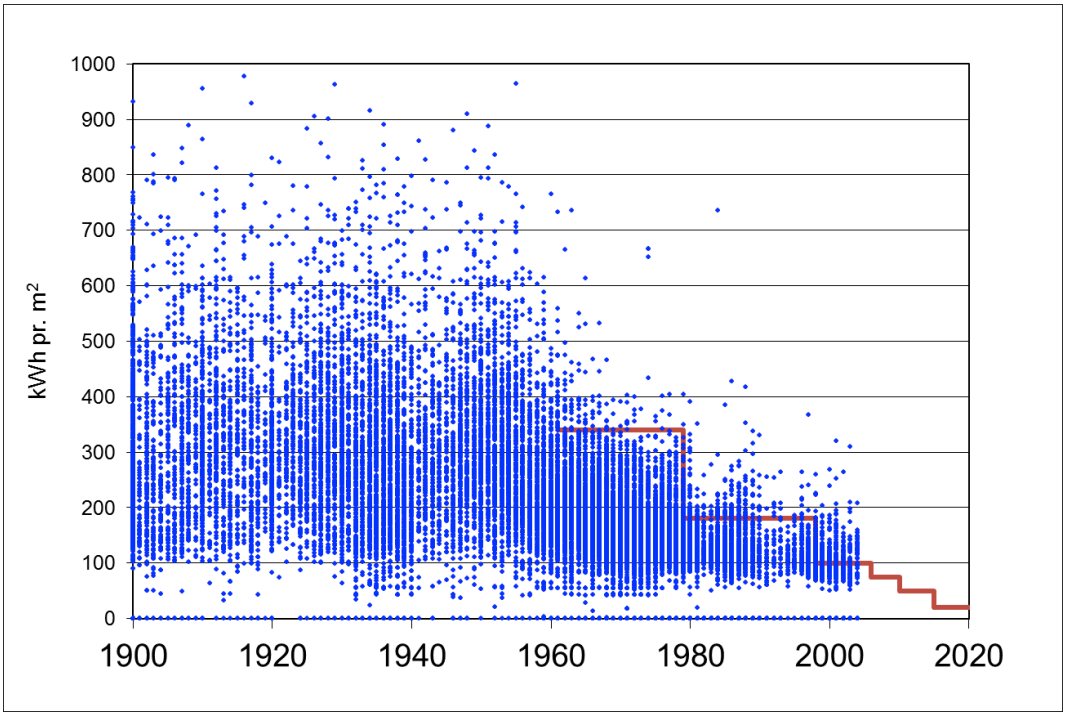

FIG 2. Measured energy consumption (dots) in Danish houses for different construction year. The red line is the requirement in the Danish Building Regulations.

Figure 3 shows that old houses have a high energy demand and large variation and new houses has lower energy demand and less absolute variation (Jensen 2004). The arrows indicate the average values. This shows that our assumptions for variations are realistic.

11.Conclusion and use in other countries

The comparison between the official Danish energy performance certification scheme and the automatic system shows that the automatic system can be used to identify buildings with potentially high energy consumption. This can be done based on information in BBR and the knowledge of typical Danish buildings. This provides a possibility of targeting incentives for better energy performance in the buildings, where you obtain the highest energy savings for the investment. The comparison with measurements shows that our assumptions are realistic.

This method can also be used in other countries using similar basic national building registers and building regulations over time, climate and information of the typical building and their use.

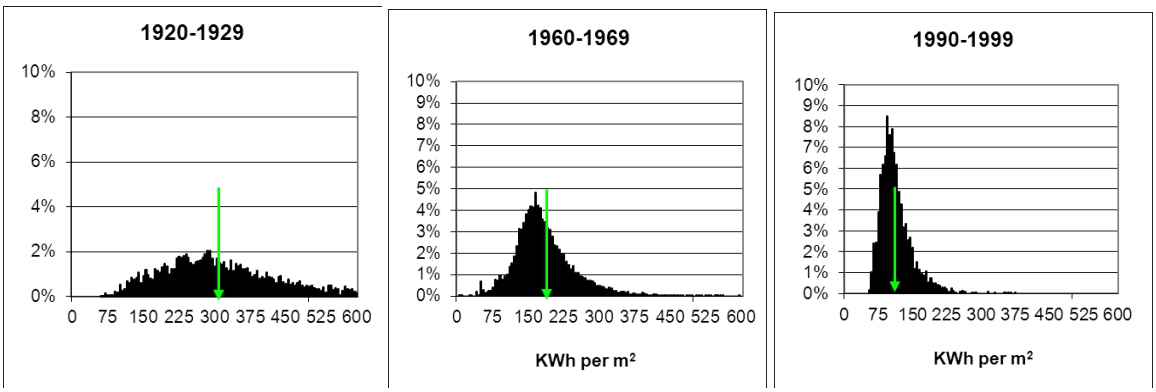

FIG 3. Variation in energy demand of houses with different construction year

References

Aggerholm, S. and Grau, K. (2005). Bygningers energibehov - PC-program og beregningsvejledning. (Building energy demand – PC program and user guide) SBi-Anvisning 213. Statens Byggeforskningsinstitut (SBi), Hørsholm, Denmark

Bertelsen, N. H., Nielsen, A., Sørensen, N.L. and Wittchen, K.B. (2011) Automatisk energirammeberegning for den eksisterende bygningsmasse (Automatic energy performace calculation for the existing buildings), SBi-rapport 2011-20, Statens Byggeforskningsinstitut (SBi), Hørsholm, Denmark

Danish Building Regulations (in Danish: BygningsReglementet. Erhvervs- og Byggestyrelsen, København. Use www.ebst.dk – to find older building regulations

EPBD (2011). Implementation of the Directive on the Energy Performance of Buildings - Country reports 2010. EPBD Buildings Platform, Brussels, European Commission ISBN: 978-92-9202-090-3.

Jensen, O. M. (2004). Barrierer for realisering af energibesparelser i bygninger. (Barriers for realisation of energy saving in buildings), Statens Byggeforskningsinstitut (SBi), Hørsholm.

Petersen, T.D. (1997). Uncertainty analysis of energy consumption in dwellings, NTNU, Dr.avh. 1997-122, Trondheim, Norway

Wittchen, K. B. (2009). Potentielle energibesparelser i det eksisterende byggeri. (Potential energy savings in existing buildings) Forskningsprojekt SBi 2009:05. Statens Byggeforskningsinstitut, Hørsholm, Danmark

Wittchen, K.B, and Kragh, J. (2012) Danish building typologies, Danish Building Research Institute, SBi 2012:01, Hørsholm, Denmark