Guideline on Documenting the Performance of Built Low Energy Buildings

Energy and Climate

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DANISH TECHNOLOGICAL INSTITUTE

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Preface

The present report is a joint work between three different projects:

- The report constitutes one of the deliverables for the milestone *Basis for methods for characterization of low energy buildings of the project "EnergyFlexHouse in the global change of the buildings industry"* financed by the Danish Agency for Science, Technology and Innovation

- The report is also part of the work of the Strategic Research Centre for Energy Neutral Buildings (www.aau.zeb.dk) financed by the Danish Council for Strategic Research, project no. 2104-08-0018

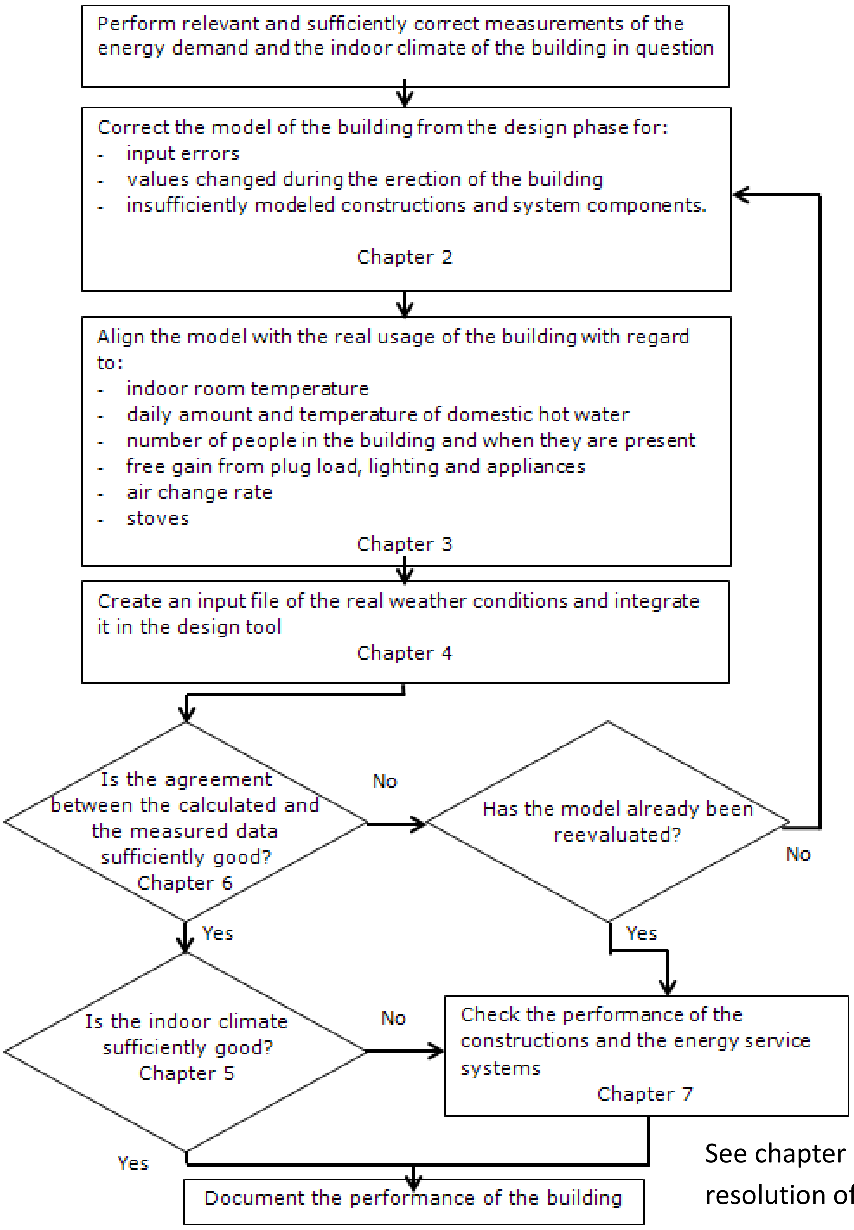
- The report is further a part of the Danish work within IEA *EBC Annex 58 Reliable Building Energy Performance Characterisation Based on Full Scale Dynamic Measurements* financed by a Danish Energy Agency, EUDP project no. 64011-0305

Summary

Unfortunately, it is often seen that new low energy buildings perform differently than expected with regards to both energy consumption and indoor comfort. The buildings often have higher energy consumption and the indoor comfort is often not as good as expected.

The report describes a method of determining if and if so why a built building performs differently from the calculations made during the design phase. The possible causes for the observed differences are numerous: the building is different from the original design, the use of the building is different from the assumptions made during the design phase, the climate differs from the weather conditions used in the design phase, there is not enough focus on the indoor climate during the design phase, components or energy service systems are defective in some way, components and system are wrongly installed and/or controlled.

The report describes a stepwise approach which goes from aligning the design phase model of the building with reality to in-depth inspection of the building components and energy service systems of the building.



See chapter 8 for a better resolution of the flowchart

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1 Introduction

It is the general experience that new low energy buildings perform differently than expected with regards to both energy consumption and indoor comfort. The buildings often have higher energy consumption and the indoor comfort is often not as good as expected. There are several Danish examples of this: the buildup areas Stenløse Syd and Fremtidens Parcelhuse, EnergyFlexHouse, Bolig for livet, as well as Komforthusene.

The reasons for the difference between the calculated energy demand during the design phase and the realized situation are typically:

- errors in the input to the design tool or the design tool cannot handle specific features of the building correctly
- changes in the design of the building and/or constructions as well as energy service systems during the building process
- other demands and usages than the standard conditions used in the applied design tool
- different climatic conditions compared to the weather data used in the design tool
- not enough focus on the indoor climate
- faults, inadequate balancing and commissioning of the building construction and the energy service systems of the building

The performance of energy efficient buildings is more sensitive to differences between the assumed and the actual design than earlier less energy efficient buildings. Therefore, it is not possible simply to compare the calculated annual energy demand with the measured annual energy demand when evaluating if a building fulfills the requirements specified during the design phase.

Based on the bullet points mentioned above, the following chapters describe a method on how to evaluate if a building performs as expected. The basis of the description is the calculation program Be10 (Aggerholm and Grau, 2011) as this program is always used in connection with the design of new Danish buildings. Calculations with Be10 are required in order to document that a designed building fulfills the energy requirements in the Danish Building code (presently BR10). However, the process described in this report may also be applied when other tools have been used during the design phase of a building. The process is shown graphically in chapter 8.

1.1 Measurements

The report deals with comparisons of calculated and measured performances of buildings. In this aspect, it is very important to obtain representative and correct measured data. Thus, it is vital to select the right measuring equipment depending on which values that are going to be part of the comparison. This means the selection of the correct number and location of sensors and meters, i.e. sensors and meters with an appropriate resolution and accuracy with regards to what will be measured. It also means the selection of an appropriate scan interval, post processing, etc.

The following methodology focuses on the comparison of calculations and measurements under the assumption that the measurements are appropriate and correct. For further information on how to design a measuring campaign please refer to (Noris, 2012). For information on appropriate sensors and meters please refer to (ASHRAE, 2002).

2 Design Tool - Be10

This chapter deals with the first two bullet points mentioned in chapter 1. As mentioned earlier, the Danish calculation program Be10 forms the basis for the comparison. However, the following method can in principle be applied on any other design, documentation or simulation tool utilized for calculation of the energy demand and indoor climate of a building.

The first step in a comparison between the designed and the real performance is to determine if the model from the design phase is still valid for the realized building, i.e. to determine if the model of the building from the design phase is still a good representation of the actual building.

2.1 Differences in Constructions and Energy Service Systems

It is often seen that building constructions and energy service systems specified during the design phase are changed during the erection of the buildings due to different reasons, e.g. a failed delivery of a certain component.

The model of the buildings should be updated with the correct values for the building components and the energy service systems which actually are present in the realized building.

2.2 Input Error

Although Be10 is a simple program, it still requires quite a large amount of input data of which several are interconnected. Thus, it is fairly easy to make input errors. Moreover, some parameters may accidentally not have been updated during the design process which means that they do not represent the finally applied constructions and system components.

For other more detailed simulation programs, the risk of making errors in the input data is of course more pronounced.

Correction of defective input data may advantageously be done together with the update of the values mentioned in section 2.1.

2.3 Incorrect Representation of Constructions and Energy Service Systems

Be10 is a very simple program which means that very complex building components and energy service systems may not be modeled correctly when using Be10. Therefore, it should be investigated if the building in question contains building components and energy service systems which are not modeled sufficiently correct by Be10.

One way of going about complex buildings components in simplified calculation tools is to leave out the complex components in the Be10 calculations and instead model the building with and without the complex components in a simulation program capable of modeling these components more correctly than Be10. The energy saving from the more detailed simulation may then be subtracted the calculated energy demand found by Be10 without the complex components.

2.4 Indoor Climate

Be10 is a one zone model meaning that if a north facing zone requires heating while a south facing zone requires cooling, the result of Be10 will be a lower cooling and heating demand than in reality. Furthermore, the room temperature may be representative of the mean temperature of the building while it may not reveal problems such as overheating in some rooms.

In order to investigate problems with thermal comfort and to get the correct heating and cooling demand, a more detailed model capable of simulating representative indoor air temperatures in relevant rooms should be applied. It is the thermal conditions and the energy demand from such simulations that preferably should be compared with measurements from the realized building or be used to correct the results of Be10 or other design tools.

3 Demands and Usage

When calculating the performance of a building during the design phase, it is necessary to make assumptions of how the building will be used when erected. These assumptions may of course differ from the real conditions when the building is put into operation. The typical assumptions made during the design phase relate to:

- indoor room temperature
- daily amount of domestic hot water and cold and hot water temperature
- number of people in the building and when they are present
- free gain from plug load, lighting and appliances
- air change rate
- stoves

Changes in these parameters between the design phase and the actual building may give rise to large differences between the calculated and the measured energy demand of the building.

In order to be able to determine if changes in these parameters are responsible for any discrepancy between the calculated and the measured energy demand, it is necessary to obtain information on the above parameters during the actual operation of the building. This is, however, not a trivial task and it demands for an effort which there normally is not funding for in a traditional building project – only in research projects.

3.1 Indoor Temperature

If Be10 is the design tool, "only" an average indoor temperature is needed for the comparison. If using more detailed simulation programs, it may be applicable to use measured time series for the indoor air temperature in representative rooms.

The standard value for the average indoor temperature in Be10 is 20°C while it is the general impression that most Danes prefer 22°C. In residential buildings, it may often be sufficient to perform a spot measurement of the temperature in the rooms even though night set back of the temperature is applied. In low energy buildings, the heat losses should be so low that the room temperature only decreases slowly during the night. In office buildings, the building management system (BMS) may be used to obtain a good picture of the indoor temperature of the building.

If time series of the indoor air temperature is needed, small cheap autonomous data loggers, each with a temperature sensor and a storage capacity of around one year with one hour logging intervals, e.g. Tinytac, HOBO, etc., may be applied. These data loggers should be calibrated so that the measured temperatures give a correct picture of the room temperature(s) in the building.

3.2 Domestic Hot Water

Domestic hot water (DHW) consumption has a large influence on the energy demand, especially in residential buildings. Furthermore, the amount of DHW differs greatly from people to people. It is, therefore, important to obtain information of the actual DWH usage in the building. This can be done over a rather short period of one or two months. As the daily tapping pattern typically will be rather constant, the results can be extrapolated to a whole year.

The best is of course to measure the amount of hot water used in the building directly together with the cold and hot water temperature. However, a heat meter capable of this is rather expensive and a data logger system is required in order to obtain time series from the heat meter. Modern heat meters typically have a built-in register where data is stored and can be read out through a computer. A cheaper but less certain solution is to install a simple manually read water meter which measures the DHW draw off together with spot measurements of the cold and hot water temperature. Often, the continuous measurements of the cold water supply to the house will indicate when people are on holiday.

However, the amount of DHW is normally not measured in buildings and it is, furthermore, quite difficult to deduct from standard measurements, e.g. remote read district heat meters, in that these give the total heat demand (space heating and DHW). If time series from a district heat meter is available, advanced statistical methods of separating the DHW demand from the total heat demand are becoming available (de Saint-Aubain et al, 2012). However, for the time being, an expert is still needed when using these methods and some development for DHW systems with a storage tank is required.

If the heating system is based on a combined space and DHW heat pump, it is much more difficult to deduct the DHW demand as the normal measurements consist of readings from the electricity billing meter which measures a combination of the electricity demand of the heat pump and any other electricity demanding devises in the building. Even if a separate electricity meter is present on the heat pump, it is very difficult to deduct the heat production of the heat pump so that the above mentioned statistical tools may be applied. The reason for this is that the COP of the heat pump for space heating and DHW are different due to the different supply temperature needed for the heating system and the DHW tank (see also section 7.2.2). Furthermore, the COP of the heat pump is dependent on the season because the source temperature is correlated with the ambient temperature. This problem is, however, being investigated in the large Danish research and innovation project iPower (www.ipower-net.dk). Thus, tools for solving this problem may be developed in the coming years and the documents on the tools developed in the iPower project will be available on www.ipower-net.dk.

Outside the heating season, the heat demand is only caused by the DHW demand. Hence, during the summer period (when avoiding the summer holydays), it is possible to obtain a good picture of the energy demand for DHW outside the heating season. This demand may also be used for the heating season if assuming identical DHW patterns.

A less certain indication of the DHW demand may be obtained if the model of the building has been corrected with regards to all other parameters than DHW in chapter 2-4 so that the calculated space heating demand is assumed to be representative for the actual space heating demand. The DHW demand may then be estimated by subtracting the calculated space heating demand from the total measured heat demand. The amount of hot water may then be calculated when using spot measurements of the cold and hot water temperature. This is, however, more calibration/fitting of the model than finding the correct DHW demand. Nevertheless, it will give an indication of the possible magnitude of the DHW demand.

3.3 Number of People in the Building

Depending on the activity level, people have a heat loss around 100 W. Thus, during the heating season, the presence of people in a building will decrease the heating demand of the building due to the free gain they deliver to the building. In buildings with a cooling load, the "free" gain from people will increase the cooling load.

In the design phase, the pattern of the presence and the amount of people in a building are not known. Therefore, standard profiles of the free gain from people are often used. However, the real presence of people may be very different from the assumption made in the design phase, - in fact, so different that it has a measurable impact on the energy demand of the building.

The patterns of the presence and the amount of people in the real building should, therefore, be investigated in order to determine if the use of the building is in fact so different from the assumptions made in the design phase that it should be taken into consideration when comparing the calculated and the measured energy demand of the building.

The standard values in Be10 are:

Residential: 1.5 W/m² or in the order of one person per 67 m² all day
Other buildings: 4 W/m² or in the order of one person per 25 m² 45 hours a week

3.4 Free Gains from Plug Load, Lighting and Appliances

Free gains from electricity consuming devises (cooker, fridge, dishwashers, washing machines, coffee machine, PCs, TVs, radios, chargers, lighting, copy machines, etc.) are as free gains from people difficult to predict in the design phase. Thus, standard values are normally applied. These standard values may be very different from the free gain in the actual building. Although electronic devises tend to be more and more efficient, people tend to have more and more of such devises both in their homes and in the offices. The electricity consumption in buildings leading to free gains is, therefore, not decreasing.

Thus, it should be investigated if the free gains from plug load, lighting, appliances and other electricity using devices are very different from the assumptions made in the design phase.

There are different ways of determining this free load. In residential areas, the measured electricity demand on the bill may be a good estimate if the electricity demand for running the building is low (i.e. no direct electric heating, heat pump, etc.) and if there is no large electricity consumption outside the building such as garden light, heated pool, etc. In office buildings, the electricity demand may anyway be split on several meters. One or several meters may only measure the electricity demand in the offices. However, general lighting may be measured together with other building related electricity demands.

In detailed simulation models, it may be preferable to use time series (e.g. hourly intervals) for the gains from plug loads, lighting and appliances rather than a fixed value in order to be able to simulate more correct temperature profiles in the rooms.

The hard way to determine the free gains from plug load, lighting, appliances and other electricity using devices is to measure the power to each devise or to look at the information at the back of the devise and multiply this value with an estimate of operation hours during the day.

The standard values in Be10 are:

Residential: 3.5 W/m² all day
Other buildings: 6 W/m² 45 hours a week – no standard value for the remaining 123 hours of the week

3.5 Air Change Rate

The Danish building code BR10 states the requirements for the ventilation flow rate and the allowed infiltration in buildings.

3.5.1 Ventilation

The standard value for ventilation in residential buildings is 0.3 l/m²s in BR10. The flow rate in other buildings depends on the actual needs of the building.

The ventilation flow rate of the building may, however, be different from the design phase, mainly due to two reasons: the demand of the building may have changed or the flow rate is for some reason not as it should be.

In both cases, it is important to define what the flow rate is. In mechanically ventilated buildings with a constant flow rate, this is done by spot measuring the flow rate in the ventilation duct works. In buildings with variable flow rate, either variable due to demand or dependent on the time of the day/week, it is necessary to establish the flow rate over a longer period of time (> week). This may be done via the BMS if such is present in the building.

In naturally ventilated buildings, the average flow rate may be determined by using tracer gas. For smaller buildings, the passive tracer gas method (Bergsøe, 1992) may be applied.

3.5.2 Infiltration

In naturally ventilated and exhaust ventilated buildings, the ventilation is the infiltration. However, in buildings with balanced mechanical ventilation systems, the infiltration is a heat loss on top of the ventilation heat loss.

The present Danish building code BR10 states a standard ventilation flow rate of 0.3 l/m^2s and a max infiltration of 0.13 l/m^2s for residential buildings. Thus, the infiltration increases the air change rate with 43% compared to the standard ventilation flow rate.

The requirement of BR10 is a heat recovery of 80% for single houses and 70% of other buildings. This means that the ventilation heat loss of the building is decreased by 70-80%, while there of course is no heat recovery on the infiltration losses. This means that the effect of an infiltration of 0.13 l/m^2s is more than twice the effect of a ventilations system with a volume flow rate of 0.3 l/m^2s and a heat recovery of 80 %.

It is, therefore, very important to determine if the measured infiltration of the building is different from the design phase (often much higher) in that infiltration have a significant impact on the energy demand of the building.

The infiltration is measured by putting the building under pressure (both over and under pressure) at 50 Pa. In small buildings, this is done by a blower door test (EN 13829, 2001) while in larger buildings, it is necessary to utilize the ventilation system of the building.

Infiltration is also caused by the opening of windows and doors. Depending of the users, this infiltration may have a large impact on the measured energy demand of the building. In large buildings with air condition, the impact of this infiltration may be very low, especially, if it is not possible to open the windows. In smaller buildings, this infiltration may have a very large impact, e.g. if the bedroom windows are left open all day long during the heating season. An interview with the users of the building may reveal how much this airing constitutes. The impact will, however, always remain rather uncertain.

3.6 Wood Stoves

Wood stoves constitute two large problems when comparing the calculated energy demand with the real energy demand of a building in that it is very difficult to determine how large a part of the energy demand of the building is actually covered by the stove.

The two problems are:

a) to determine the heat actually produced by the stove
b) how large part of a) is actually beneficial for the building

a) It may be possible to determine how many m³ biomass, e.g. pieces of wood, that are annually used for heating, but it is not possible to determine this at much smaller intervals. In order to determine the energy contents of the biomass, it is necessary to know its calorific value. A rough estimate may be given if the exact type of biomass together with the water content is known. However, the problem does not stop here. In order to be able to calculate the heat from the stove, the efficiency of the stove also needs to be known. This efficiency will vary depending on the way in which the firing is performed in the stove. Hence, only a rough estimate may be obtained.

A stove should preferably have its own air intake from the outside in order not to disturb the designed air change rate in the building. If this is not the case, the stove will increase the infiltration in the building in order to obtain sufficient oxygen for the firing. If the air change rate is not increased sufficiently during operation of the stove, it will result in problems with poor combustion, and thereby lower efficiency, as well as pollution and backwards draft in the stove, which causes smoke in the building. The additional infiltration is very difficult/impossible to determine if not using tracer gas. Furthermore, the draught through the chimney, when the stove is not in use, can be significant if the stove is not tight.

b) Even though the heat from the stove may be calculated correctly, this is often not the heat production which should be added to the other measured heat productions in order to give the total heat demand of the building. Firing in a stove tends to lead to indoor air temperatures higher than the normally wished temperature of approximately 22°C. This means that a part of the heat from the stove leads to overheating which is not directly valuable for decreasing the heat demand and may even lead to excess ventilation is order to get the room temperature down. However, some of the overheating increases the temperature of the constructions of the building. A part of this heat is regained when the stove gets cold and the indoor air temperature drops to the normal level.

Based on the above, it is seen that stoves constitute a large problem when trying to compare the calculated and the real energy demand of a building. Up till now there does not exist a good method for going about this problem besides trying to give an estimate on the energetic benefit of using a stove based on experience.

One thing, however, that is easy to measure is when a stove is in operation. This can be done with a temperature sensor - that can withstand high temperatures - on the stove.

3.7 Conclusion

The actual use of a building and the behavior of its future users are often not known very well during the design phase of the building. Thus, the actual energy demand of a building may differ rather much from the calculated energy demand at the design phase. Examples show that for identical houses, one family may have twice as high an energy demand as the neighbor (Andersen, 2012).

The standard values for usage and user behavior often lead to a lower energy demand than measured. However, if the standard values are not aligned with reality, it is wrong to state that the building performs worse than expected, i.e. if the increased energy demand is due to changes in the conditions which the building are exposed to and not due to problems related to the constructions and systems of the building.

Prior to the comparison, the model of the building needs to be aligned with the actual conditions which the building is exposed to.

It is often difficult to obtain the information mentioned above. Hence, it is often beneficial to start with performing parametric studies with the design model for the parameters described in this chapter in order to determine which parameters are the most important to investigate and if some parameters do not need to be determined precisely.

4 Climate

In the design phase, a standard weather data set for the location is normally used for the calculation of the energy demand of the building; Be10 uses e.g. the Danish Design Reference Year (DRY) (Jensen and Lund, 1995).

The climate during operation may, however, be very different from the weather data used during the design of the building. In Denmark, the weather has become more extreme since the development of the Danish DRY due to climate changes. Figure 1 shows the development of the heating degree days (HDD) and the solar corrected heating degree days (solar corr. HDD) for Denmark since 1990 compared with the values obtained from the Danish DRY. It is seen that the climate has become warmer, except for 1996, 1997 and 2010, while the influence of solar radiation on the degree days (the absolute difference between the blue and red curve in figure 1) changes from year to year and is higher than the DRY, except for 2006.

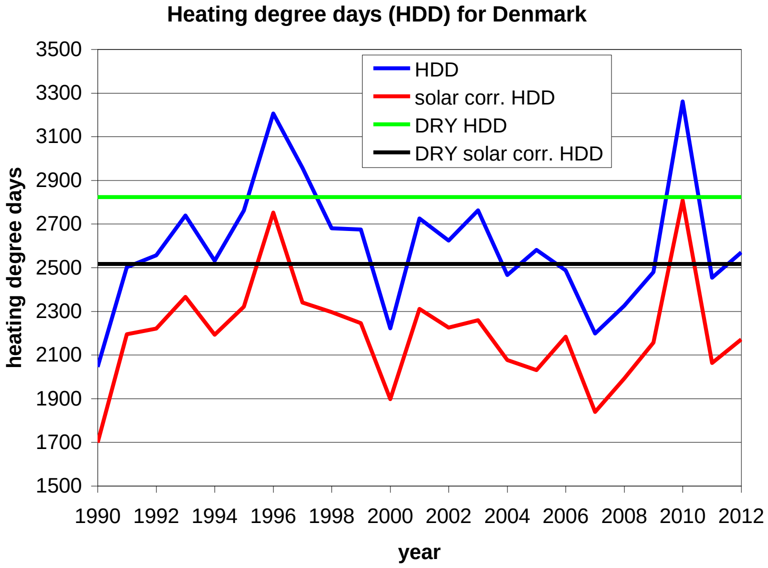


Figure 1: The development of the heating degree days and solar corrected heating degree days for Denmark since 1990 compared with the values obtained from the Danish DRY.

Higher ambient temperatures and more solar radiation will ceteris paribus lead to a lower heating and a higher cooling demand.

Many simulation programs and design tools are capable of using measured weather data instead of a standard climate file. However, it is necessary to transform the measured data into a format that the tools may read. Moreover, when planning the measuring campaign, it is necessary to insure that the climate values required by the design tool are measured using appropriate precise meters and sensors and with the right scan interval (usually hourly intervals). For Be10, the Danish Building Institute may for a smaller fee transfer measured climate data into a weather data file which Be10 can utilize.

5 Indoor Climate

Buildings should not only be built in order to minimize their energy demand, - they should first and foremost be built in order to create comfortable conditions for people (and to protect their belongings). However, it is often the impression that during the design phase, the indoor climate is third compared to architecture and energy demand. Unfortunately, this often results in a poor indoor climate, especially in office buildings, but also often in the last years attempt to build nearly-zero and Net zero energy homes.

The European standard (EN 15251, 2007) states that *"An energy declaration without a declaration related to the indoor environment makes no sense. There is therefore a need for specifying criteria for the indoor environment for design, energy calculations, performance and operation of buildings."*

The standard (EN 15251, 2007) specifies how design criteria can be established and used for the dimensioning of systems. It defines how to establish and define the main parameters to be used as input for building energy calculation and long term evaluation of the indoor environment. Finally, it identifies parameters to be used for monitoring and displaying the indoor environment.

Guidelines focusing on the indoor environment in nearly-zero and Net zero energy buildings may be found in (Olesen et al, 2013). A questionnaire may be applied in order to obtain the opinion of the users of the building. Examples of questionnaires may be found in (Olesen et al, 2013).

The main parameters to evaluate are:

- Temperature
- Draft
- Humidity
- Air quality
- Daylight
- Acoustics

To fully evaluate the indoor environment, it is necessary to measure the following in representative rooms:

- Indoor air temperature (preferably at different locations in the room)
- Air speed
- Humidity
- Air quality in the form of CO_2, particles, VOCs, etc.
- Lux and daylight factors
- Reverberation time

6 Comparison

After the model of the building has been aligned with the real conditions with regards to input values, user demand and pattern as well as the climate, it is possible to obtain a more correct comparison of the calculated and the measured performance of the building. However, the first year of measurements in a building may not show the real picture of the performance of the building.

The European standard (EN 15603, 2008) states: *"It is recommended that the first one or two years after the erection of the building are discarded. The energy use during the first years is often larger than during the following years for several reasons:*

- *some additional energy is used to dry the building fabric;*
- *adjustment of control system may not be perfect from the first day of use;*
- *there may be some faults that are corrected during the first year."*

Furthermore, some sensors and meters may not have been located and operated correctly from the start of the measuring campaign. The measurements should, therefore, carefully be investigated with regards to incorrect measurements, e.g. missing data, faulty values and outliers.

Although the model has been aligned with the real conditions, the model will most certainly not give the same results as the measurements in that the model - although it might be very detailed – is only a rough approximation of the real building and the use of it. The uncertainty band of the measurements should also be taken into consideration. A discrepancy within ±10% will often be an acceptable agreement.

If the discrepancy between the calculated and the measured performance is too large, the steps done in chapter 2-4 may be reevaluated to detect any overlooked errors. If this does not lead to an improved result, the discrepancy may be due to incorrect performance of the constructions and the energy service systems of the building. Thus, the next logical step will be to determine which constructions and/or energy service systems that lead to the observed large discrepancy. However, in-depth investigations of constructions and energy service systems normally require detailed knowledge and measurements on as well as inspections of any suspect components and systems. This is dealt with in the following chapter.

6.1 Metrics for Comparison

In the present report, the metrics for comparison is primary energy as this is the metrics given in the Danish Building code. However, other metrics may be the basis for the comparison as well, e.g. end energy use, CO_2 equivalent, cost, etc. Moreover, the energy demand of the user, i.e. not a building related energy demand, may or may not be included in the comparison. The tool developed in IEA SHC Task 40/ECBCS Annex 52 Towards Net Zero Energy Solar Buildings (Belleri, 2012a and 2012 b) provides the possibility to compare calculations with predictions for two cases and several weighting methods:

- Nearly-zero energy buildings (nZEB) as defined by the recast of EBPD (EU Commission, 2010) without user related energy demand

- Net zero energy building (NZEB) where all energy demands of the buildings are included

- In both cases, the metrics are:
  - Primary energy, both using static, asymmetric and strategic primary energy factors
  - CO_2 equivalents
  - Cost

7 Errors in Constructions and Energy Service Systems

Detection of malfunctions of the constructions and energy service systems often requires great skills in the constructions/systems being investigated. Furthermore, it requires detailed measurements and inspections. Hence, it is often a non-trivial and expensive task to carry out.

The following is not an exhaustive description of how to detect construction and energy service system malfunctions, but it is more a list for inspiration. The description is mainly aimed at smaller buildings. A detailed description of what may go wrong in a large office building can be found in (Jensen et al, 2010).

7.1 Thermal Envelope

The thermal envelope consists of opaque and transparent constructions where the opaque constructions are walls, roof and floor slap while the transparent constructions mainly are windows and sometimes doors.

Typically, it is rather difficult to determine the performance of the thermal envelope. The following three subsections describe some methods which can be applied when checking the opaque constructions, windows/doors and the overall performance of the thermal envelope.

7.1.1 Opaque Surfaces

It is difficult/impossible to determine if the construction of opaque surfaces is carried out correctly without performing destructive testing where a part of the surface is opened in order to allow for an inspection of the materials inside the construction.

Thermography of the surface may reveal if there are cold bridges in the construction or any inhomogeneity that should not be present.

The U-value of a construction may also be evaluated using a heat flux sensor. However, the obtained values will only be representative for the small area where the heat flux sensor is located. It is, therefore, very important carefully to select the location of the heat flux sensor.

When performing tests concerning the infiltration (section 3.5.2) with e.g. a blower door and when the building is under pressurized, it is with a smoke stick or thermography possible to determine if there are any cracks in joints (wall/wall, wall/ceiling, wall/floor and wall/windows/doors) and/or holes in the internal cladding (e.g. at electrical sockets, penetrations of tubes, etc.).

7.1.2 Windows

Nowadays, windows and doors normally have a unique id-number. This number makes it possible to trace the products back to the manufacturer in order to determine if the products are in fact the right products which have been installed.

Typically, windows are identified in terms of three values: U-value, g-value and light transmittance. The light transmittance can be measured by having a lux sensor at each side of the window.

It is only the larger part of the g-value (the direct transmitted solar energy) which can be measured by a pyranometer on each side of the window. However, this will give an impression of the g-value.

The U-value of the window (not including the framing) may be measured with difficulty by using heat flux sensors during stable conditions without sunshine. The U-value of the framing is very difficult to verify. However, 2D heat flow calculations may give an idea if the actual constructions comply with the assumptions made during the design phase – if the drawings of the actual cross section of the framing can be obtained from the manufacturer.

Moreover, it is possible to determine where the low-E coating is located on the glazing. In buildings with cooling demand, the glass with low-E coating should not face the room as this glass is excess heated by solar radiation absorbed in the low-E coating.

The gas in-between the glasses of the windows may be analyzed by taking out a small sample using a thin needle. However, this is more like destructive testing.

For openable windows, the sealing strip may be evaluated in the same way as when detecting cracks in opaque constructions (section 7.1.1).

7.1.3 Overall Performance

There exist several methods to obtain the overall UA-value of a building based on measurements. One drawback of the methods described in the following is that the infiltration and ventilation are included in the obtained "UA-value". Other measurements are, therefore, necessary in order to determine the ventilation/infiltration losses (see sections 3.5 and 7.3).

7.1.3.1 Coheating

"A coheating test is a method of measuring the heat loss (both fabric and background ventilation) in W/K attributable to an unoccupied dwelling. It involves heating the inside of a dwelling electrically, using electric resistance point heaters, to an elevated mean internal temperature (typically 25 °C) over a specified period of time, typically between 1 to 3 weeks. By measuring the amount of electrical energy that is required to maintain the elevated mean internal temperature each day, the daily heat input (in Watts) to the dwelling can be determined. The heat loss coefficient for the dwelling can then be calculated by plotting the daily heat input against the daily difference in temperature between the inside and outside of the dwelling (ΔT). The resulting slope of the plot gives the heat loss coefficient in W/K." (CeBE, 2010).

(CeBE, 2010) describes the test procedure and the necessary sensor set in details, but it does not describe how to deal with incoming solar radiation through the windows during the test period. However, the influence of solar radiation through windows may be limited by screening off the windows using opaque white foil.

"For separating the heat loss due to ventilation/infiltration (CeBE, 2010) recommends: When analysing the results obtained from a coheating test it is often useful to be able to separate out the heat losses attributable to the fabric and those attributable to background ventilation. This can be achieved by undertaking two pressurisation tests on the dwelling, one prior to undertaking the coheating test and one as soon as the test has been completed. The resulting average air leakage rate can then be used to give an estimate of the background ventilation rate for the dwelling. Alternatively, the background ventilation rate within the dwelling can be measured during the coheating test using tracer gas decay methods." (CeBE, 2010).

In buildings with mechanical ventilation, the ventilation system should be shut down and the inlets and extractions should be sealed during the test.

The test should not be carried out before the drying out of the fabric has stopped, otherwise too large UA-values will be obtained. A coheating test requires one to three weeks of unoccupancy.

7.1.3.2 Analysis of Time Series

Analysis of time series is a way to obtain the UA-value of a building when occupied. This demands for longer measuring periods, but as the occupants are not influenced by this, it does not pose a problem. The method requires measured daily mean values of the space heat demand, the ambient temperature and the solar radiation. If only the total heat demand is measured, the DHW demand should be subtracted by using the method described in section 3.2.

Based on statistical methods, it is then possible to obtain the UA-values including ventilation/infiltration. The likely heat loss from infiltration and ventilation in natural ventilated houses may be found as described in the former section. If the building is mechanically ventilated, the ventilation flow rate may be measured as described in section 3.5.1.

If wind speed and direction are measured, the method may also be used to investigate if the building is sensitive to wind, e.g. if sealing strips of the windows and doors are performing poorly.

An example of the method applied on several buildings may be found in (ENFOR, 2010).

7.1.3.3 Combined Coheating and Analysis of Time Series

More information on the building may be obtained if the two methods described above are combined when the heating of the building is intentionally out of phase with the outdoor climate, e.g. the building is heated even though it is not necessary due to a high ambient temperature and solar radiation or the building is not heated even though it is freezing outside. This will decorrelate the heating from the weather and make it possible to determine e.g. the thermal capacity of the building which may be used to optimize the control of the heating and cooling system. It is also important when investigating Smart Grid; when there is a need to shift the heating load from periods where the grid is overloaded to periods with excess energy in the grid. An example of this method may be found in (Backer and Madsen, 2010).

One disadvantage of the method is that due to the decorrelation of the heating with the weather, the building cannot be occupied during the test period. The length of the test period depends on the thermal mass of the building; the more the thermal mass → the longer the test period – usually in the order of two to three weeks.

7.2 Heating System

In large parts of the world, it is necessary to heat buildings in order to maintain a good thermal indoor climate during the winter. There exist many types of heating systems. In Denmark, the main heating supply systems are district heating (in 2012: 60% of the heating demand) and boilers (natural gas and oil). The political agenda in Denmark states that boilers will be replaced by district heating and heat pumps before 2035.

7.2.1 District Heating

A thorough check of a district heating substation demands for an expert.

The district heating utilities usually specify the temperatures and pressure differences which they can deliver. In many Danish district heating systems, a supply temperature of 70°C in winter and 60°C in summer are guaranteed. However, variations exist and in the Greater Copenhagen area as well as in the rest of Europe, supply temperatures are generally high. Water pressure levels and available pressure differences at the consumer vary as well.

The district heating water can be supplied directly into the heating system of the building if pressure and temperature levels are low (< 6 bar and 85°C) or indirectly with a heat exchanger in between the district heating side (primary side) and the building heating system side (secondary side).

Usually, the heating system and the domestic hot water heaters must be designed to deliver low district heating return temperatures back to the district heating system in order to get the most efficient operation of the district heating production facilities and distribution networks. Utilities can require a certain maximum return temperature (e.g. 40°C) delivered back to the system by a building owner.

In this respect, the following must be evaluated:

- Substation design and settings
- Domestic hot water system
- Space heating systems

7.2.1.1 Substation Design and Settings

Check if the substation fulfills the design and utility requirements and operation conditions.

Make notes on all regulator valve positions, controller settings including circulation pump settings and write down the name plate information.

Some simple tests can help check if the installation is working properly:

For indirect systems (with heat exchanger):

- The temperature set point on the secondary side must be at least 5 K lower than the district heating flow temperature on the primary side

- The difference between return temperature on the primary and secondary side of heat exchanger must be 5 K at the maximum

For all systems:

- Has the pressure difference regulator if present been adjusted?

- Are the temperature sensors for the regulators placed correctly?

- Has dirt filters been cleaned?

- Does the available pressure difference on the district heating side match the required pressure difference?

In order to check if the return temperature is low enough, the average temperature difference for a season can be calculated from the heat meter data. Taking the accumulated water volume and the accumulated energy into consideration, the difference is simply calculated in terms of:

$$860 \text{ x accumulated energy in MWh / accumulated volume in } m^3$$

A comparison of this temperature difference with the guaranteed delivered temperature of the district heating utility can help evaluate if the return temperature is as expected.

7.2.1.2 Domestic Hot Water Systems

Domestic hot water can be produced in a storage water heater with a tank and a coil heat exchanger or in an instantaneous water heater with typically a plate heat exchanger.

For storage water heaters:

- The coil heat exchanger must be designed for a large temperature difference and a low flow (compared to e.g. coil heat exchangers for boilers). If the return temperature is high, a flow limiter can be added

For instantaneous water heaters:

- In areas with high calcium content in the water, hot water temperatures above 55°C should be avoided

7.2.1.3 Space Heating System

The space heating system must be designed for district heating; for radiator systems, typically a temperature set of 70°C/40°C or in areas with low temperature district heating e.g. 55°C/25°C. This will allow for a low return temperature. Floor heating systems will normally deliver a low return temperature, which for a well-designed system should not exceed 30°C.

In doubt about the capacity of the heat emitting systems, a more detailed evaluation of radiator capacities or underfloor heating layout must be carried out.

7.2.2 Heat Pumps

A thorough check of a heat pump demands for an expert.

However, some areas may be evaluated by non-heat pump experts:

- Size of the heat pump
- Set points of the heat pump
- Heat absorbing system
- Heat distribution systems

In general, in order to obtain a high efficiency (COP) for a heat pump, the ΔT between the source and the necessary temperature to the heat emitters should be as low as possible.

7.2.2.1 Size of the Heat Pump

Determine if the size of the heat pump is suitable for the building.

If the heat pump is too small compared to the heat demand of the building, the heat pump cannot deliver the required supply temperature to the heat distribution system, e.g. underfloor heating system or radiators during cold periods. In order to meet the heat demand of the house, it is necessary for the heat pump to switch on the built-in resistant heating element. This will drastically decrease the COP of the heat pump.

A too large heat pump compared to the demand may lead to an increase in COP if the heat pump is frequency controlled (i.e. it is controlled to always match the heat demand by adjusting the rpm of the compressor). However, the COP of an on/off controlled heat pump will decrease due to many starts/stops which increase the capacity losses of the heat pump. Many starts/stops will also increase the wear on the heat pump.

7.2.2.2 Set Points of the Heat Pump

Check if the set points of the heat pump are correct.

The temperature set point for the supply temperature of the heat pump to the DWH tank and the space heating system should be as low as possible while still satisfying the comfort demands of the occupants in the building. Make sure that the ambient temperature compensation of the supply temperature to the space heating system is adjusted to fit the demand of that particular building and that the temperature of the DHW is not higher than necessary (see section 7.2.2.4).

Increasing the supply temperatures lead to decreasing COP of the heat pump.

7.2.2.3 Heat Absorbing System

Determine if the heat absorbing system is sufficiently large for the heat pump.

There are several potential sources of the heat pump. However, in Denmark, the source is normally the ground or the ambient air.

The heat exchange between the source and the cooling circuit of the heat pump should have such a size that a small ΔT between the source and the gas coming out of the evaporator is obtained. A too small heat transfer leads to a too low evaporation temperature and thereby a higher ΔT between the source and the supply temperature to the heating systems as well as a decrease in COP.

For ground coupled heat pumps, problems may be due to:

- Too little length of the tubes in the ground
- Too little distance between the tubes in the ground
- Too low flow rate in the tubes in the ground
- Too low heat transfer to transport a sufficient amount of heat due to the thermal properties of the soil

For heat pumps using the air as source, problems may be due to:

- A too small evaporator (heat exchanger with refrigerant located outside)
- Dirt on the air side of the heat exchanger
- Too low air flow through the heat exchanger
- The fan is always running; not only when the heat pump is running
- Icing on the evaporator because the heat pump is not designed for cold regions
- The ambient environment (i.e. not energy related): the fan and/or the refrigeration system is too noisy

7.2.2.4 Heat Distribution Systems

Determine if the heat distribution system is dimensioned correctly.

It is very important that the supply temperature to the heat distribution systems (DHW tank and underfloor heating/radiators) is as low as possible.

A too low flow rate in the distribution system will lead to an increased outlet temperature. However, a too high flow rate may lead to noise in the distribution system.

7.2.2.4.1 DHW

The supply temperature to the DHW tank is determined by the wished DHW temperature: for bathing >40°C and for kitchen >45°C. Furthermore, for protection against legionella, the temperature of the DWH tank should be raised to 60°C at regular intervals. The DHW temperature may need to be higher (due to heat loss) if the tap points are located far away from the DHW tank. Moreover, circulation of the DHW water may be necessary in order to decrease the waiting for sufficient hot water at the tap point. This will lead to increased losses, decreased COP and increased wear of the heat pump. The insulation of the DHW pipes should, therefore, be checked.

High DHW temperatures lead to decreased COP for the heat pump. Thus, the set point temperature should be as low as possible but still maintain the necessary comfort. The heat loss from a circulation circuit will increase the need for heat to the DHW tank at a high temperature. Hence, circulation on the DHW should be avoided if possible.

7.2.2.4.2 Space Heating

The supply temperature to the space heating system should be as low as possible meaning that the outlet temperature should be controlled based on the heat demand of the building, e.g. represented by the ambient temperature.

Floor heating systems will normally require a lower supply temperature than radiators. If the flow rate in the distribution system is too low, the only way to meet the heat demand is to increase the supply temperature which will decrease the COP of the heat pump.

7.2.2.5 Measurements related to Check of Heat Pumps

- The COP may be checked by simultaneous measurements of the heat delivered from the heat pump and the electricity used by the heat pump
- The heat absorbing system may be checked by measurements of the flow rate in the heat exchanger together with the supply and the return temperature. This is, however, difficult if the heat exchanger is an air to refrigerant type
- The heat distribution system may be checked by measuring the flow rate and the supply and the return temperature

However, the above investigations demand for a heat/flow meter in the heat distribution system and in the heat absorbing system. Heat and flow meters are unfortunately rather expensive both as components and the installation.

7.2.3 Boilers

A thorough check of a boiler demands for an expert.

Usually, modern gas- and oil-fired boilers are sold as combi-boilers with a built-in instantaneous water heater or as boiler-storage tank sets where the boiler and the storage tank are designed to work together. Not much can be done besides securing that the controller is set correctly.

Make notes on all regulator valve positions, controller settings including circulation pump setting and write down the name plate information.

In Denmark boilers have to be checked at regular intervals (annually or biannually) by a certified installer with regard to efficiency and CO_2 emission.

7.3 Ventilation Systems

A thorough check of a ventilation system demands for an expert.

The energy demand for transportation in a mechanical ventilation system may be checked by measuring the flow rates in the system and the electricity demand of the fans. For the measuring of air flow rates (and air temperatures) in ducts, please see (Johansson and Svensson, 2007).

If too low flow rates are measured this may be due to several reasons: that the initial adjustment of the system was incorrect, that in and outlets from the rooms and to/from ambient are in some way blocked, that filters are dirty, etc.

The efficiency of a passive heat exchanger may be checked by measuring the flow rates and the in- and outlet temperatures for both air flows. If the heat exchanger is very efficient, icing on the exhaust side will occur during cold periods. It should be checked that the de-icing is working correctly. It should also be checked if the bypass of the heat exchanger is functioning correctly so that the heat exchange only occur during the heating season - and maybe during hot periods if the indoor temperature is lower than the ambient temperature, so that the fresh air is cooled.

If the heat recovery unit of the ventilation system includes a heat pump with exhaust air as the heat source and where heat is used for heating the fresh air and/or the DHW, please refer to section 7.2.2.

In buildings with variable flow rate, either variable due to demand or dependent on the time of the day/week, it is necessary to investigate the performance of the ventilation system over a longer period of time (> week) in order to determine if the flow rate of the system comply with the expectations. This may be done via the BMS if such is present in the building.

If hybrid ventilation (mechanical ventilation in combination with natural ventilation) is utilized, it should be checked that the mechanical ventilation system is only used when necessary.

If night cooling is applied, it should be checked that the night cooling system is only running when overheating is present or foreseen.

7.4 Cooling Systems

A thorough check of a cooling system demands for an expert.

Check of a cooling system is in many ways similar to the check of a heat pump. The check consists of:

- Size of the cooling system
- Set points of the cooling system
- Measures taken for the prevention of simultaneously heating and cooling
- Cooling distribution system
- Heat rejection system

However, before checking the aspects mentioned above, it should be determined if (as designed) the cooling demand is as low as possible. This means checking the amount of free gains (sections 3.3 and 3.4), if the overheating protection is working correctly (section 7.7) and if cooling by natural ventilation and night ventilation is functioning (section 7.3).

A too small size of the cooling system will, as for heat pumps, normally lead to a decreased efficiency (EER).

The outlet temperature (of the cooling system) of the cold (often) water should be as high as possible in order to decrease the ΔT between the cold and the warm side of the cooling system.

The cooling distribution system should have a sufficient high flow rate and capacity in order to keep the outlet temperature from the refrigeration system as high as possible.

The heat removal system should have a sufficient high flow rate and capacity in order to keep the outlet temperature from the refrigerator as low as possible.

For cooling in general, problems may be due to:

- A too small heat exchanger located outside
- Dirt on the air side of the heat exchanger
- A too low flow rate on both sides of the heat exchanger
- The fans are always running, not only when the refrigerator is running
- If direct cooling is possible (at low ambient temperatures, the compressor does not need to run. Only a pump is needed to circulate water between the dry cooler and the cooling surface in the rooms or in the ventilation system), it should be investigated if this feature is operating and at the right set points
- Too noisy compressor and fans (not energy related)

7.5 Lighting

Many buildings, especially larger buildings, have building integrated lightning.

It should be checked if the power demand and the lux level in the rooms are as specified during the design phase.

If automatically controlled lighting, it should be checked if the lights in fact are switched on and off as specified.

7.6 Solar Energy

One way of decreasing the energy demand of a building is to have an energy production on the building or the building site based on renewable energy. The Danish Building regulation (BR10) allows that the energy produced by thermal solar energy systems, PV or micro wind turbines can be subtracted from the energy demand of the building. As micro wind turbines are hardly used in Denmark, only solar energy will be dealt with in the following.

As for the other energy systems, a thorough check of solar energy systems demands for an expert.

7.6.1 Solar Thermal

It is normally very difficult to determine if a built thermal solar energy system performs as designed. This normally requires that at least one heat meter is installed in the system and that the solar radiation on the same plane as the solar thermal collectors is measured. As both instruments are expensive, they are normally not available.

In order to determine the efficiency of the solar collector array, it is necessary to simultaneously measure the energy flow from the array with the solar radiation on the array. To conduct a more thorough investigation, it is necessary to measure the volume flow rate and the inlet/outlet temperature of the liquid to the solar collector array. These latter three values are often seen as output of a heat meter.

In order to determine the overall performance of a solar heating system, it is necessary to measure all energy flows to and from the storage tank of the system and preferably also several temperatures. In a DHW system, this may demand for three heat meters: from the collector array, the energy tapped from the tank and from the auxiliary heating of the top of the tank. Combined space heating and DHW systems demand for even more heat meters and temperature sensors.

The run time and the power consumption of the pump for the solar collector array may be checked using an electricity meter. If the backup is a built-in resistant heater in the tank, the energy demand of this heater may also be checked using an electricity meter.

One very simple but not very informative check of a solar heating system is to check if the pump of the collector array starts and stops as expected. This check can normally be done via the display of the controller of the solar heating system where it is often possible to see the temperatures of the solar collector array as well as the bottom and top temperature of the DHW tank. The check is simply to determine if the pump starts and stops at the designed temperature difference between the collector and the bottom of the DHW tank. This check states, however, absolutely nothing about the efficiency and the heat production of the collector circuit.

Another simple and more informative test is to empty the DHW tank for hot water by replacing it with cold water in the morning on a sunny day. The temperature difference between the morning and afternoon temperature of the tank together with the volume of the tank will give an estimate of the efficiency of the system, especially if the accumulated solar radiation during the day is known/measured, e.g. from a nearby meteorological station.

7.6.2 PV

It is normally easier to determine if a PV system performs as expected. The actual power produced by the system can usually be displayed via the inverter of the system. The efficiency of the system may then be found if the actual solar radiation on the PV panels is measured simultaneously with a portable pyranometer.

If the PV system does not perform as expected, there is a need for an expert to determine the cause; both because skills are necessary and because of safety reasons as the current of a PV system often can be fatal.

Thermal imaging may reveal if cells/panels are not performing. However, it is often necessary to measure the current and voltage together with the solar radiation for each panel or series of panels in order to determine which panels are not performing as expected. Specialized equipment for the latter is available but costly.

7.7 Overheating Protection

If the heat gains from solar radiation, people and electrical devices/appliances are large, the building may be in danger of overheating. If overheating occurs, there will be a need for cooling of the building in order to maintain a good comfort level. If the overheating is profound, a mechanical cooling system (see section 7.4) may be necessary. Otherwise, solar screening and cooling by ambient air may be sufficient.

Even if a mechanical cooling system is necessary in a building, the cooling load should be reduced as much as possible in order to decrease the energy demand for cooling. If solar screening and cooling by ambient air were part of the design of the building, it should be checked if these features function as assumed.

7.7.1 Sun Screening

Sun screening may either be fixed or movable. Fixed sun screening is e.g. outside fixed lamellar, MicroShades (www.photosolar.dk/pages/default.asp), sun screening film in the windows etc. Movable solar screening may be internal/external Venetian blinds, shutters, movable lamellar, curtains etc.

The first thing to do is to check if the designed sun screening is present. If not, this explains any overheating problems and increased energy demand for cooling. If present, the performance of the sun screening should be checked - which can be tricky. However, start with checking that it is the correct products which are installed. For automatically movable sun screening, the control of the sun screening should be checked. For manually sun screening, it should be determined how people in the building actually operate the sun screening.

7.7.2 Cooling by Ambient Air

Cooling of a building by ambient air can be performed via mechanical ventilation and/or by natural ventilation. In both cases, the control of this ventilation should be checked; i.e. that the cooling by ambient air actually happens when there is a need for it.

In combination with the investigation of the indoor climate, it should be investigated if the cooling with ambient air leads to draft problems which should be avoided.

When cooling with ambient air via a mechanical ventilation system, it should be checked that the fresh air is not heated more by the heat exchanger or the heating system than what is comfortable. A too high inlet temperature of the fresh air decreases the cooling potential of the air.

7.8 Combined Control

Many of the energy service systems described above are present in a building and they interact with each other which means that there is a risk of them working against each other. In larger buildings, the control of several systems may be combined in order to decrease the energy demand of the building and to secure the indoor climate. However, small errors in the control strategy may lead to increased energy demand and poor indoor climate instead (Jensen et al, 2010).

Therefore, it is important to check the control system(s) of a building. Especially, because many design tools assume perfect control of the energy service systems. Large discrepancies between calculated and measured energy demand may, therefore, be due to incorrect control. Check of the control in large and larger buildings may, however, be rather time consuming.

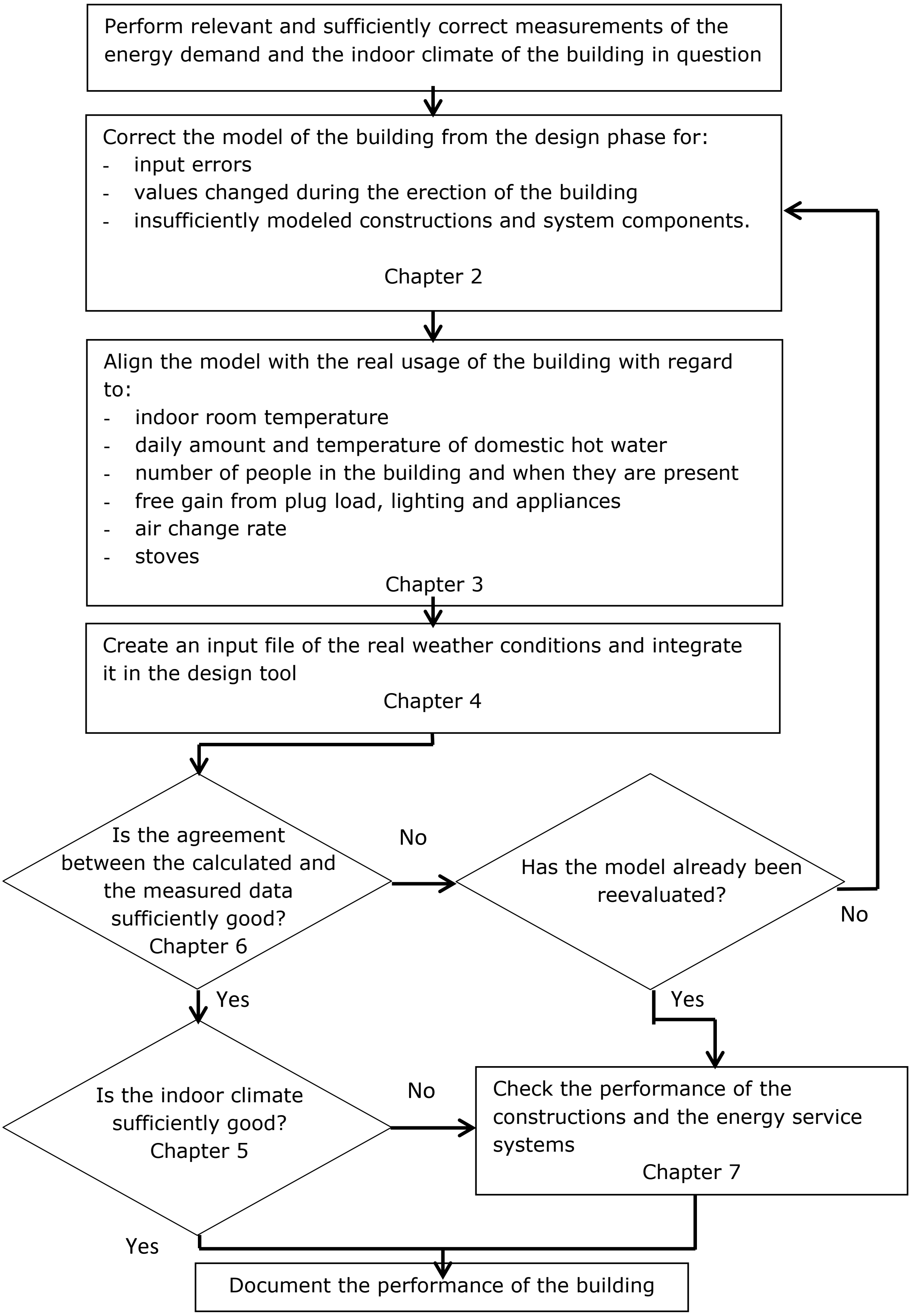
7.9 Conclusions

The sections above show that it can be very time consuming and expensive to check building constructions and energy service systems in a building. Furthermore, even more detailed investigations than those described in the previous sections may be necessary in order to pinpoint errors in systems and in the control of the systems. This leads to the conclusion that constructions and systems should be designed, installed and commissioned correctly from the start. It is cheaper to make it right from the start than to correct errors afterwards. However, for the time being there is no requirements in Denmark for using an independent commissioning agent to insure proper installation and commissioning.

The sections above can be used as an inspiration of what may be wrong and how to detect this. However, in order to keep the expenses down, it is important to start with the most likely causes for the deviations between expectations and real life. This is, however, a skill that is mainly developed from experience.

8 Brief Overview of the Methodology

The methodology described in the former chapters is briefly outlined in the following flowchart:



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