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Energy and indoor climate measurements in Denmark's first energy neutral block of flats

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Abstract. Denmark's first energy neutral multi-family house, BOLIG+, is constructed at Søborg near Copenhagen and consists of 10 flats divided on 4 floors. BOLIG+ was the first attempt to construct a multi-family block of flats that complies with a set of criteria and dogmas that defines the BOLIG+ concept. Energy production on the building needed e.g. to meet not only the buildings energy demand, but also the residents' electricity energy use for light and appliances. Additionally when exchanging energy with the grid, energy "sold" should have at least the same exergy level as energy "bought". Building multi-family houses that are energy neutral on annual basis, is, therefore, much more difficult than for a single-family house. One of the reasons for this is the small amount of roof area available (per. dwelling) for local electricity production compared to the roof area of a single-family house. Last, but not least, the buildings was constructed under normal economical market conditions, i.e. without any subsidies for the construction.

When designing the building, the normal standard conditions for calculating the buildings energy performance was offset in order to ensure better coherence between the design energy demand and the following energy measurements. The indoor temperature was set higher, and so was the domestic hot water demand. Additionally, free loads (gains) from persons, light and appliances was set lower than the standard.

To meet the goal of being energy neutral, several low-energy solutions are used e.g. compact thermal envelope; highly insulated constructions; highly insulating windows; hybrid decentral ventilation; heat recovery on grey wastewater; PV on facades and roof; buffer zones. Additionally, an electric battery was installed to improve the economy of the PV installation by optimizing the amount of electricity used inside the meter (tackling the feed-in tariff issue).

This paper presents results from 1½ year of measurements of energy performance and indoor climate carried out in the building during the period 2017-2018.

Measurements of energy consumption showed that if the PV installation has produced as expected and the residents had used electricity as expected, the building would have been only 11% from being energy neutral.

Indoor climate measurements show high temperatures in a large share of the period.

1. Introduction

The BOLIG+ [1] concept was initiated at the Danish Energy Camp 2005 and developed through 2006-2007 and concentrates around six dogmas:

- Zero Energy Building (ZEB) on annual basis, including auxiliary electricity for private household and lightning,
- intelligent and user-friendly,
- flexible – in use and over time,
- good and healthy indoor climate,
- high architectural quality, adapted to the local context,
- constructed on ordinary economic market conditions.

2. BOLIG+

In the design process, there has been a close collaboration between architects and engineers, plus other relevant parties, e.g. utility companies, urban planners, sociologists, etc. This resulted in a thoroughly processed building concept that focused on all six dogmas. Additionally, all aspects of the building had been scrutinized for possible cost and energy optimization, sometimes exploiting alternative measures such as a lift as replacement of an elevator. This resulted in a design for a block of flats that should produce the same amount of primary energy as is used for operating the building plus the occupants' use of electricity for light and appliances.

2.1. Design and construction

From the developer, it was a demand to have balconies at each flat, however due to heavy traffic the municipality required closed balconies. This challenged the overall economy and the available space for PV on the facades. The architectural design of the facades was then a game in which windows, PV and balconies must be part of a harmonious whole. The PV installation on the roof will only be able to produce just over half of the building's energy needs, so PV panels on facades towards the southeast and southwest are a necessity. This challenge helped to foster the idea of designing the building's facade as a game between light and dark fields – similar to a chessboard.

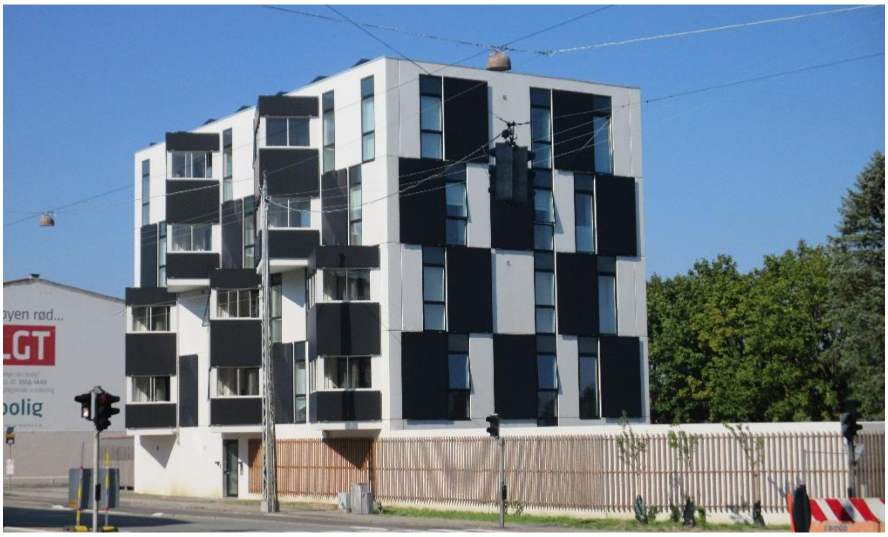

Figure 1. BOLIG+ seen from Southeast.

2.2. Obtaining energy neutrality

The secret behind a very low energy consumption is integrated design. When looking at the building it looks like many other modern buildings, but all solutions have been selected carefully and can be summarised as:

- compact and well insulated thermal envelope,
- airtight building,
- effective decentralized mechanical ventilation,
- hybrid ventilation in the summer,
- heat recovery from grey wastewater,
- electricity production via multiple PV panels,
- connection to local district heating grid.

Up front, it was decided to keep the roof surface free of installations, allowing maximum space for PV panels placed on the roof with minimum stands. This affected several other installations, e.g. exhaust and inlet of the ventilation were located in the facades and the elevator was replaced by a lift, i.e. no elevator shaft raise over the roof. A lift also had some energy and economic effects, as it was both cheaper and more energy-efficient due to less expected use.

During the contest and the early design process many different solutions were investigated, such as ground connected channels, electricity production from rainwater running in barrel drains, dynamic facades, high-efficient insulating materials, solar walls etc. However, they were all found to be economically heavy to integrate. The project team experienced that, in order for BOLIG+ to meet the economic constraint, it was necessary to utilize passive solutions instead of new and often costly technology. The limitations on economy thus had the effect that integrated design was fully exploited.

Two heat supply solutions were investigated, namely district heating and heat pump. With an estimated heat pump COP of 3.5, it would be the optimum primary energy solution. A heat pump solution would need less primary energy and thus less PV. Taking into account that a district heating solution required more PV area, the two solutions were estimated to have approximately the same economy (plant plus operating costs). In the Table 1, varying primary energy factors over time are shown. However, the local district heating company had a provision which stated that in connection with the establishment of new main lines, no connection fee had to be paid. This made the district heating solution the most economically advantageous solution. And since the space needed for PV was highly critical, district heating was then the possible, reliable and, in a Danish context, politically opportune choice.

Table 1 Varying primary energy factors in Denmark

	2008-2010	2010-2015	2018-
Electricity	2.5	1.8	1.9
District heating	1.0	0.6	0.85
Other	1.0	1.0	1.0

Due to the new Danish feed-in tariff structure, there is a large price difference between selling and buying electricity (approx. 0.27 €/kWh) from the grid. Therefore, an experimental vanadium redox flow-battery [2] was installed to improve the overall private economy for operating the building, by storing the electricity from time of production to time of use.

3. Energy and indoor climate measurements

Measuring energy and indoor climate in a building is a comprehensive and costly task and without support from the ELFORSK programme [3], it would not have been possible to establish a measuring campaign. Never the less, measurements also relied on the needed measurement systems in the building to be able to bill the occupants and to comply with requirements for metering stated in the European directive on energy efficiency [4].

In the flats, indoor climate was logged using WiFi loggers in 2 rooms, logging indoor temperature, humidity and CO_2. In addition to this, the total electricity consumption, electricity from every outlet (incl. decentral ventilation unit) were measured. Space heating was measured, incl. forward and return temperature of the heat circulation. The consumption cold water and the position of the door to the balcony were further measured.

Centrally, in the boiler room, the following measurements were carried out: total district heating delivered to the building (incl. forward and return temperatures) and district heating to the domestic hot water tank; heat recovery from grey wastewater; electricity to hot water tank to fight Legionella; electricity to and from the PV flow battery; total electricity in and out of the building; billing meters for the 10 apartments; electricity used on common spaces; electricity production from 4 PV systems; water temperature in top of tank and flow of space heating in flats; outdoor temperature.

Weather was taken from an existing nearby weather station located at Danish Technological Institute in Taastrup.

3.1. Comparing calculated and measured energy

It is often seen that new buildings have a different and often higher energy consumption than calculated in the design phase. In addition, the indoor climate in the buildings is often not as good as expected. It is a commonly known fact, that a building in use has a higher energy consumption than calculated during the design phase. There are many reasons for this:

1. input error in the calculation program used or that the calculation program cannot handle specific components of the building correctly,
2. changes in the design building and/or constructions and installations during the construction phase,
3. other use of the building, including other occupational behaviour than assumed in the calculations, e.g. increased room temperature,
4. real weather differs from the design year used,
5. lack of focus on indoor climate both in the design and construction phase,
6. faults in and poor commissioning of structures and installations.

Because of the above, it is typically not possible to assess whether a building functions as calculated simply by comparing the energy consumption calculated in the design phase with the measured annual energy consumption during operation. It is necessary to adjust the calculations relative to the actual conditions. How, a calculation program is adjusted to the current conditions, is described in detail in [5] and [6]. In [5] is also described, how to troubleshoot to determine which components and/or installations which results in a higher measured energy consumption for the building also after adjusting the calculation program.

4. Results

To meet the BOLIG+ dogmas, a building must comply with the requirements for being a Building class 2020 building according to the Danish Building regulations 2015 [7], but without contribution from locally produced electricity, i.e. a highly insulated passive solution. Additionally – to accommodate points 3 and 5 above - more realistic indoor temperature, internal loads, and domestic hot water consumption should also be part of the calculated energy demand.

Besides the demand for energy performance, there were also demands for focus on the indoor climate, including punishment by overheating and requirements for daylight conditions.

In the following, mainly the heating demand of the buildings is evaluated.

The design tool Buildings energy demand 2010 (Be10) [8] estimated an annual heating demand of 43.5 MWh while the real annual heating usage was measured to 47.3 MWh. This is only a 9 % higher heating demand than anticipated during the design. So, within the uncertainty of the calculation and the measurements the building performs as it should – or does it? This is investigated in the following.

Table 1 shows some of the input parameters to Be10 during the design phase (left column) compared to the same parameters measured in the actual building (right).

Table 2. Input parameters to Be10 during the design phase compared with the actual measured values. 1) Volume of DHW is decreased because of heat recovery on the grey wastewater from bathrooms.

	Design	Measured
Room temperature	20 °C	22.8 °C
Heat gains from persons	1.5 W/m²	1.03 W/m²
Heat gains from appliances	3.5 W/m²	2.4 W/m²
Mechanical ventilation	0.32 l/s/m²	0.347 l/s/m²
Infiltration	0.07 l/s/m²	0.064 l/s/m²
DHW	175 l/m² 1)	162 l/m² 1)
Temperature of DHW	55°C	54°C

Table 1 shows that the indoor temperature was higher than foreseen, while the heat gains were lower. The mechanical ventilation airflow rate was a bit higher, while the infiltration rate was a bit lower. Both DHW consumption and the temperature of the DHW was a bit lower in the actual building. Furthermore, the total solar radiation was almost the same as in the weather file in Be10, while the ambient temperature most of the time was higher. The number of heating degree-days in the actual year was 3033, while in the weather file in Be10 it is 3200.

When introducing the measured values from table 1 and a milder climate in Be10 the calculated heating demand changes from 43.5 MWh to 36.8 MWh, which is much lower than the measured: 47.3 MWh.

When investigating the measurements it is observed, that the actual buildings has a heat consumption for floor heating in the bathrooms during the summer, which normally isn’t considered in a Be10 calculation for determination if a building comply with the Danish Building Regulation. It was further observed, that the length of the pipes were large and that the heat exchangers of the ventilation systems was slightly less efficient in the real building compared to the original Be10 model. When including the summer floor heating and the heat losses from the extra piping/a bit less efficient heat exchangers the calculated heating demand increased to 43.8 MWh. As the model now only calculates a 7 % too low heating demand, it was judged that it was not necessary to adjust the model further.

Some of the input values are now set to the standard values: room temperature to 20°C, heat gains to 1.5 and 3.5 W/m² (see table 1) and a higher DHW demand of 250 l/m² (minus the effect of heat recovery on the grey wastewater from the bath rooms) and without floor heating in the bathrooms during the summer. This leads to an annual heat demand of 29 kWh/m² while the heat demand in the design case was 28 kWh/m². So, overall the building performs as expected with regard to heating demand although the demand was distributed differently when compared to the original calculation. The calibration of the model hereby led to an insight, which otherwise would not have been possible.

The electricity use for operating the building was a bit higher in the real building compared to the design calculation: 2.1 vs. 1.8 kWh/m². The combination of the heating demand of 29 kWh/m² and an electricity demand of 2.1 kWh/m² leads to a primary energy demand of 29*0.6+2.1*1.8 = 21.2 kWh/m², which is only 6 % higher that the aim of 20 kWh/m². So, within the uncertainties, the building did perform as expected.

Was the building energy neutral with all the PV panels on the facades and roof? Well, the PV panels produce 26 % less than expected and the occupants used a bit more electricity in the apartments, so the building was not energy neutral. However, if the PV panels had produces as designed, and the electricity use in the apartments was as defined in the design phase, the building would only be 11 % from being energy neutral, which is actually a very good result.

More information on BOLIG+ and the performed energy calculations can be found in [3].

5. Discussion
BOLIG+ is the first example of how far, in terms of energy neutrality, it is possible to go regarding energy neutrality for a block of flats, under Danish climate and market conditions. However, not all energy conservation measures on the building may in itself be cost optimal and better societal energy economics may arise if some of the investments were moved to central energy production instead of local sub optimization.

Introduction of an in house electrical battery storage is far from optimal from an overall energy efficiency or CO_2 elimination point of view. But, due to the current feed-in tariff structure in Denmark, it may be economical feasible to optimise the electricity consumption inside the meter.

6. Conclusions
Did the building meet the BOLIG+ dogmas?

The building would almost have been energy neutral, given the photovoltaic system had produced the planned amount of electricity and the residents had used a little less electricity, in accordance with the BOLIG+ requirement of 1725 kWh/dwelling per year. The building meets the Building class 2020 energy performance requirement as defined in the Danish Building regulations 2010/2015 without contribution from local renewable electricity production. This highlights that the building itself has a very good energy performance, created by utilizing simple and well-known measures. However, the evaluation also highlights that without the resident's involvement in correct use of the building, it is not possible to meet the target.

During winter, there is a good indoor climate in the building in terms of in-door temperature and CO_2 level. However, some residents complain about dry air during the heating season, which unfortunately is a natural consequence of having an adequate air-change. During summer, the moisture and CO_2 level are satisfactory, but overheating occurs in several of the rooms. The rooms most exposed to overheating are the ones that faces northeast and thus get a large amount of morning sun. It is expected that the overheating issue could have been reduced by introduction of external solar shading – especially as the natural ventilation proved insufficient to reduce the problem.

It is possible for the residents to control several systems in their flats; however, an insufficient information level has been an issue for some systems. Especially, information on the ventilation system was insufficient resulting in often-wrong use of the systems. As a contrast, information about the intelligent power outlets and control of these has been sufficient and several residents have customised the programming of the system.

The building fits the local energy infrastructure as it is heated by district heating. The building can in the future provide service to the surrounding electricity grid, as it is equipped with a battery (connected to the PV system) that can be charged and discharged according to the amount of electricity from renewables in the grid. Weather the building, with its black and white sections on the facade, fits into the local architecture dominated by red masonry houses is of course a matter of taste, however, it is undiscussable that the building is a landmark at the top of the hill where the building is situated.

By utilizing simple and well-known technologies, it has been possible to construct BOLIG+ at Søborg on ordinary economic market conditions.

Has BOLIG+ reached its goal regarding energy neutrality?

For BOLIG+ the direct comparison of the designed energy demand and the actual energy consumption led to the same overall conclusion as the calibration exercise, i.e. that the building performs as expected. However, the calibration exercise gave an insight to the actual energy flows in the building, which otherwise would have remained hidden. The actual use of the building and a milder climate lead to a lower energy demand, which was counterbalanced by not originally considered floor heating in the bathrooms during the summer and more heat losses from piping and slightly less efficient heat exchangers in the ventilation systems than in the original model of the building.

Bearing in mind that it is the first attempt to construct a multi-family block of flats in accordance with the BOLIG+ dogmas, the results is quite remarkable. Not all dogmas are fully met, but sufficient to demonstrate that the BOLIG+ dogmas can be good references for residential buildings in the future.

7. Acknowledgements

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Arkitema Architects designed the building in close collaboration with MOE consulting engineers.

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