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Possible explanations for the gap between calculated and measured energy consumption of new houses

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Abstract

The overall aim to reduce CO_2 emissions has brought the energy requirements for new houses into focus. The question is whether the stepwise tightening of the energy requirements for new houses has had the expected impact on the actual realized energy consumption. In the news media, headlines at regular intervals state that new houses do not perform as expected with regard to energy consumption based on a simple comparison to the building class (energy frame). The gap is sometimes explained by a higher indoor temperature than used in the standard calculation or more generally by resident's "careless" energy behavior. However, this may not be the full explanation and there may be other reasons for the difference. Or more specifically: Does the theoretical calculated energy demand, based on standard assumptions and without taking into account the effect of variations in e.g. hot water consumption, internal heat gains or construction faults, underestimate the actual energy consumption in general? As an example, the registered measured energy consumption for heating and hot water of approximately 800 new houses was compared to the calculated energy demand. The analyzed energy consumption data show that a significant share of the houses consumes more energy in a simple comparison with the theoretical energy frame based on standard assumptions. The objective of the study was to find and evaluate possible explanations/reasons for this gap between the theoretical calculated energy demand based on standard assumptions and the real-life registered measured energy consumption for new houses. It includes an evaluation of the possible impact on the energy demand caused by deviations from the standard assumptions for a series of parameters like indoor temperature, hot water consumption, internal heat gains, U-values, thermal bridges and ventilation rates.

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Keywords: Energy consumption, heating consumption, energy frame, calculated heating demand

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1. Introduction

At regular intervals headlines in the news media state that new houses do not perform as expected with regard to energy consumption based on a simple comparison to the building class (energy performance rating) [1]. When it comes to new houses, the gap is usually explained by a higher indoor temperature than used in the standard calculation or more generally by resident's "careless" energy behavior. Such a comparison is shown in Figure 1, where an analysis of approx. 800 new single-family houses' registered measured heat consumption divided according to their building class; A2010, A2015 or A2020 as defined by the Danish Building Regulations [2]. The evaluation of the houses was established by using data stored in two main building registers in Denmark – the Building Stock Register [3] and the Energy Performance Certificate (EPC) Scheme Register [4]. The comparison shows that there is a tendency towards under-performance, particularly concerning the newest building classes (see right graph in Figure 1), however this is not a fair evaluation of the performance as the deviation in the assumed fixed boundary conditions has a significant effect on the theoretical calculated supply energy demand.

Usually the discussions in the media do not examine in depth the cause of these differences between measured and calculated consumption. The energy class calculation for new houses follows more or less the same standards and methods as used for energy ranking of buildings. This method however, must be both robust and simple to keep the price of certification reasonable. The primary reason for energy labelling of buildings is to make the energy performance of different buildings comparable for buyers and to suggest relevant energy-saving initiatives to the house owner. Behind the energy performance rating is a theoretical calculated energy demand for supply heating and electricity (for building operation only) under fixed standard conditions, used to rank the house on a scale (e.g. in Denmark: A2020, A2015, A2010, B, C, D, E, F, G).

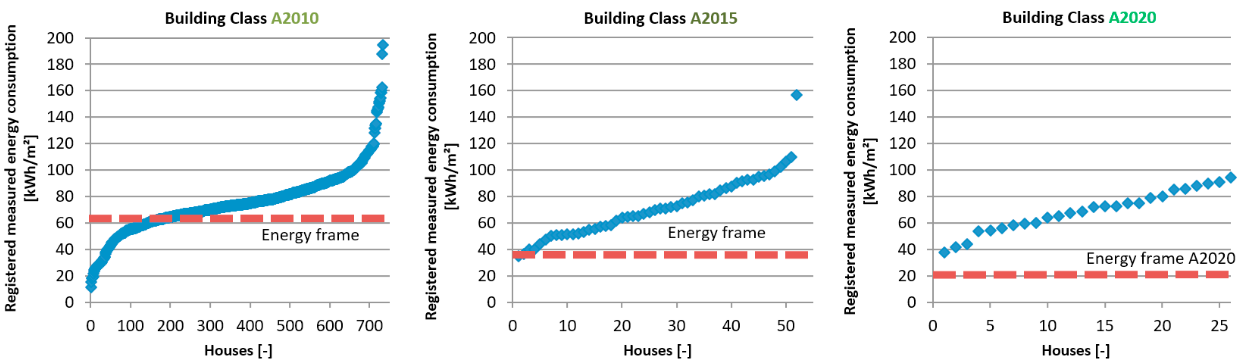

Fig. 1. Unfair comparison of the energy frame and registered measured energy consumption for room heating and hot water in 811 single-family houses erected between 2010 and 2013, heated by either district heating or natural gas. The heated area is between 75 and 300 m². The data have been adjusted for degree days and only realistic consumptions between 10 and 200 kWh/m², data span at least 300 days are shown (outliers 21). T

2. Method

The analysis of the possible impact on energy demand of deviations from the standard boundary assumptions of a series of parameters performed in this paper is based on the program, Be15 [5] and a simulation model of a typical single-family house attached with the program. The single-family house complies with Building Class A2015 and the main input data of the model are presented in Table 1.

Table 1. Main data of Be15 model.

Heat supply	District heating		Windows U-value	1.05	W/m²K
Heated area	180	m²	Glazing (double) g-value	0.62	-
Hot water consumption	250	l/m² per year	Ceiling U-value	0.09	W/m²K
Heat capacity	120	Wh/K m²	Wall U-value	0.16	W/m²K
Ventilation (air change)	0.32	1/s m²	Floor U-value	0.08	W/m²K
Heat recovery	88	%	Foundation ψ-value	0.09	W/m²K

3. Comparable figures

When discussing the reasons for a gap between measured consumption and calculated energy demand, it is an obvious precondition that the two figures should be comparable. It is often seen that the measured heating consumption is compared directly to a simple conversion of the energy class of the house. As the value behind the energy class is based on demand for supply energy calculated by using different primary energy factors reflecting the efficiency to produce heat or electricity, this makes direct comparison impossible without making adjustments. Figure 2 gives an overview of the calculation of the total supply energy demand used for ranking the house on an energy ranking scale.

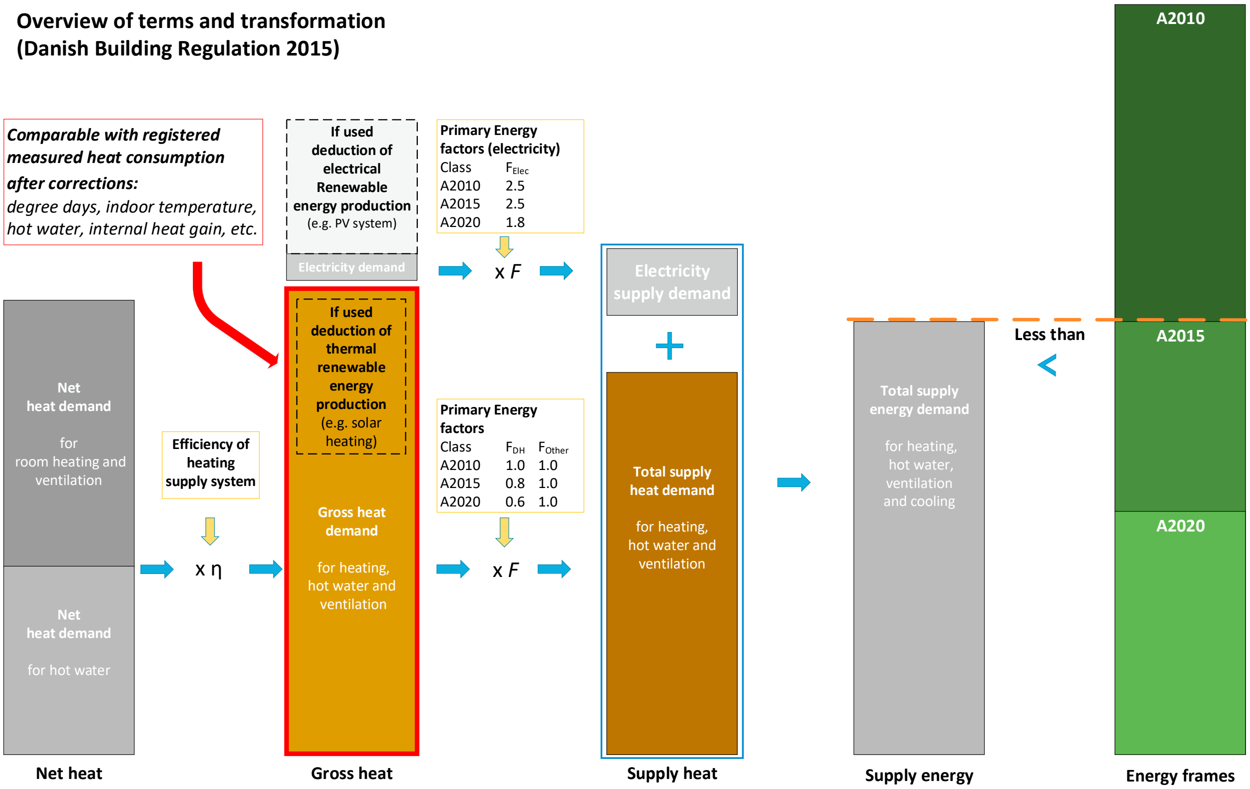

Fig. 2. Terms and transformation calculating the total supply energy demand by use of primary energy factors.

In new houses heated with district heating or a natural gas boiler, the electricity consumption for building operation is typically used for circulation pumps and ventilators in a mechanical ventilation system. This is typically a limited consumption (compared to the total energy consumption) though as seen in Figure 2 the consumption is multiplied with an energy factor of 2.5 and therefore of higher impact.

4. Indoor temperature

When explaining the gap between the calculated and the measured energy consumption, the deviation of indoor temperature from standard conditions is often given as the main explanation. According to the Danish Building Regulations, an indoor temperature of 20 °C should be used. This assumption could be a realistic average value in an old house, where primary rooms like kitchen, bathrooms and living room may be heated to 21-23 °C and other secondary rooms like hall, bedrooms or scullery may only be heated to 18-19 °C. In new houses, a more even indoor temperature must be assumed due to well-insulated building envelopes. In Table 2 the effect on the calculated net heating demand (excluding hot water) is presented. It is seen that the effect of increasing the indoor temperature in new high-insulated houses has a relatively significant influence.

Table 2. Calculated net room heating demand (excluding hot water), gross heating demand (including hot water and efficiency of the heating system) and the total supply energy demand (where heating is multiplied by 0.8 and including electricity for operation multiplied by 2.5) for the basic house model A2015, at indoor temperatures above the standard value of 20°C.

Indoor temperature	Net room heating demand	Increase	Gross heating demand	Increase	Total energy demand	Increase
[°C]	[kWh/m²]	[%]	[kWh/m²]	[%]	[kWh/m²]	[%]
21 (+1°C)	25.7	16.8	41.1	9.6	38.5	8.1
22 (+2°C)	29.9	35.9	45.3	20.8	41.9	17.7
23 (+3°C)	34.5	56.8	49.8	32.8	45.5	27.8

5. Hot water consumption

The hot water consumption in a house is of course very dependent on the number of residents and their bathing habits. It is a general perception that younger people bathe more compared with the elderly. Similarly, it is also a general perception that the average age of the residents of the new houses are lower than in older houses. Therefore, it could be assumed that in general, the energy used for hot water in new houses is underestimated compared with the rest of the housing stock; however, measurements of hot water consumption are rarely documented in literature, especially for new houses. This input to the calculation of the energy demand therefore introduces a high uncertainty and since the energy consumption for hot water represents a higher share of the total heating demand in new houses compared to old houses, the effect on the calculation result is relatively higher.

According to the Danish Building Regulations the standard energy demand calculation assumes a fixed hot water consumption of 250 l/m² per year for dwellings. However, hot water consumption is dependent on the number of residents rather than the heated area. According to a survey [6], the average consumption of water in Danish households was 106 l/day per person. It is often assumed that 1/3 of this is for hot water resulting in a hot water consumption of 35 l/day per person. If we assume 2 parents and 2 kids in a household this will result in a consumption of 4 x 35 l/day x 365 day / 150 m² = 340 l/m² per year. As this is based on an average consumption for all generations, the consumption in a younger family could probable be much higher. Table 3 shows the effect on the heating and energy demand of increased hot water consumption in new houses.

Table 3. Calculated net heating demand for hot water, gross heating demand (including hot water and efficiency of the heating system) and the total supply energy demand (where heating is multiplied by 0.8 and including electricity for operation multiplied by 2.5) for the basic house model A2015, at different levels of hot water consumption above the standard 250 l/m² per year.

Hot water consumption	Net hot water heating demand	Increase	Gross heating demand	Increase	Total energy demand	Increase
[l/m² per year]	[kWh/m²]	[%]	[kWh/m²]	[%]	[kWh/m²]	[%]
300 (+50)	18.1	16.8	40.1	6.9	37.7	5.9
350 (+100)	20.7	33.5	42.7	13.9	39.8	11.8
400 (+150)	23.3	50.3	45.4	21.1	41.9	17.7

6. Internal heat gain

The standard internal heat gain from people and equipment including lighting are fixed values of respectively 1.5 W/m² and 3.5 W/m² according to [2]. In new houses, this contribution to the heat balance has a significant effect on the total supply energy demand as it corresponds to (1.5+3.5) W/m² x 6000 h (heating season) = 30 kWh/m² per year. If this is not taken into account, the supply energy demand would be significantly higher.

This raises the question whether fixed values for heat gains are representative for new houses? The average single-family house area has increased from approx. 150 m² in 1975 to above 200 m² in 2015 [8] corresponding to an increase of 33%. If assumed that new houses in average are occupied by the same number of people as old houses, the heat gain from people should consequently be reduced by 33% (0.5 W/m²) in new houses.

According to the Danish Energy Agency, the electricity consumption for a 180 m² house with 2 adults and 2 children is 4900 kWh per year [9] corresponding to 3.1 W/m². This is lower than the fixed standard value assumed for electrical equipment (3.5 W/m²). The electricity consumption in a new house, where kitchen appliances and lighting is highly energy efficient, might be even lower. Table 5 shows the effect of deviation in the internal heat gain.

Table 5. Calculated net heating demand (excluding hot water), gross heating demand (including hot water and efficiency of the heating system) and the total supply energy demand (where heating is multiplied by 0.8 and including electricity for operation multiplied by 2.5) for the basic house model A2015, at different levels of internal heat gain. Standard heat gain is 5 W/m².

Internal heat gain [W/m²]	Net room heating demand [kWh/m²]	Increase [%]	Gross heating demand [kWh/m²]	Increase [%]	Total energy demand [kWh/m²]	Increase [%]
4.0 (-20%)	25.7	16.8	41.1	9.6	38.6	8.4
4.5 (-10%)	23.9	8.6	39.3	4.8	37.1	4.2
5.5 (+10%)	20.1	-8.6	35.6	-5.1	34.0	-4.5
6.0 (+20%)	18.3	-16.8	33.8	-9.9	32.5	-8.7

7. Building envelope U-values

In the calculation model, the transmission heat loss through the building envelope is typically divided into these main types; ceiling, walls and floor with a corresponding theoretical calculation of the U-values. In new houses, U-values are calculated before the building is erected and therefore changes during the building process (e.g. use of other insulation products than originally planned) will obviously add uncertainty to the actual U-values. In carefully performed U-value calculations these are corrected for thermal bridges, however under the practical construction work there could easily be small areas where the insulation layer is reduced for example due to placement of technical installations such as ventilation ducts etc. Therefore, the uncertainty of the theoretically calculated U-value and the corresponding actual U-value must be assumed to be high with a resulting higher heat loss coefficient than expected. In addition, the linear thermal transmission loss for the assembly of floor, wall and foundation causes a high risk of differences between the theoretical assumption and practical construction work, as it is a relatively complex assembly both to calculate and to construct.

The transmission heat loss through windows is normally well known; however there could easily be changes in the delivery of window products (e.g. glazing, mullions, transoms) with some effect on corresponding U- and g-values. Table 6 shows the individual effect if some part of the building envelope does not, for some reason, correspond to the original assumptions.

Table 6. Calculated net room heating demand (excluding hot water), gross supply heating demand (including hot water and efficiency of the heating system) and the total supply energy demand (where heating is multiplied by 0.8 and including electricity for operation multiplied by 2.5) for the basic house model A2015, at 5% increase of the U-values/Ψ-value.

Building envelope U-value increased by 5%	Net room heating demand [kWh/m²]	Increase [%]	Gross heating demand [kWh/m²]	Increase [%]	Total energy demand [kWh/m²]	Increase [%]
Ceiling	22.4	1.8	37.9	1.1	35.9	0.8
Wall	22.5	2.3	38.0	1.3	36.0	1.1
Floor	22.3	1.4	37.7	0.5	35.8	0.6
Thermal bridge foundation (Ψ-value)	22.2	0.9	37.6	0.3	35.7	0.3
Windows	23.1	5.0	38.6	2.9	36.5	2.5

8. Other possible deviations

In new houses, the heat gain from solar radiation through windows is a very important contribution to the energy balance. The solar radiation is of course very dependent on shading from the surroundings such as neighboring buildings, trees and high bushes, especially in the wintertime where the sun is low in the sky. The assumptions regarding shading factors can therefore have a significant effect on calculation results as shown in Table 7, where the impact of a relatively modest increase of the horizon shade angle from 10 to 15 and 20° is shown.

The actual ventilation air change rate is another factor that may vary significantly in practice, as it is both difficult to regulate and make regular checks of the performance. The heat recovery performance could also be lower than expected and the electricity consumption for ventilators higher, however this has not been analyzed in this work. Table 7 shows the effect of a higher ventilation air change rate.

Table 7. Calculated net room heating demand (excluding hot water), gross heating demand (including hot water and efficiency of the heating system) and the total supply energy demand (where heating is multiplied by 0.8 and including electricity for operation multiplied by 2.5) for the basic house model A2015.

Horizon shade angle (standard 10°).	Net room heating demand [kWh/m²]	Increase [%]	Gross heating demand [kWh/m²]	Increase [%]	Total energy demand [kWh/m²]	Increase [%]
15°	23.6	7.3	39.1	4.3	36.9	3.7
20°	25.2	14.5	40.7	8.5	38.3	7.6
Ventilation air change rate (Requirement 0.5 1/h)						
+10%	22.4	1.8	37.8	0.8	36.3	2.0
+20%	22.7	3.2	38.2	1.9	37.0	3.9

Other possible reasons for deviations between the registered measured and calculated energy performance of new houses could be caused by air tightness and airing/venting and technical installations not performing as expected.

9. Conclusion

For new single-family houses with a very low heating demand the effect of even small deviations from the standard fixed boundary conditions may significantly increase the total heating demand:

- Increase due to higher indoor temperature (21° – 23°) 10 – 33 %
- Increase due to higher hot water consumption (300 – 400 l/m²) 7 – 21 %
- Increase due to lower level of internal heat gain (4.0 – 4.5 W/m²) 5 – 10 %
- Increase due to U-value uncertainty of each building part (+5 %) 0.3 – 2.5 %
- Increase due to higher level of shade from the surroundings (15° – 20°) 4.3 – 8.5 %
- Increase due to higher ventilation air change rate (+10 – 20%) 0.8 - 1.9 %

For new single-family houses, the analysis shows that the reason for the higher registered measured heat consumption compared to the theoretical standard calculation energy demand, as often reported by the media, could easily be explained by realistic deviations from the standard assumptions for the energy calculation. In total, deviations may well generate an extra consumption of 25-80%, largest for the building assigned the strictest energy performance requirements. However, this work does not suggest or conclude that the fixed boundary conditions should be adjusted for new houses, as the consequence would further complicate comparing performances of different buildings. Nevertheless, as this study clearly demonstrates, it is important to be careful before concluding that new houses do not perform as expected especially when this is done by comparing the registered heating consumption to the Building Class energy frame.

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