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**Sustainable buildings
and energy utilization
in cold climate zone**

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Editors

Energy-efficient Building in Greenland: Investigation of the Energy Consumption and Indoor Climate

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SUMMARY

Recently, a brand new single family home was built in Sisimiut, Greenland. The building was constructed as a wooden house typical for Greenland. However, some non-traditional measures were implemented in order to reduce the energy consumption and improve indoor air quality. Assessment of the influence of these measures is essential for their implementation on a wider scale. In particular, functionality of the state of the art ventilation system is of large concern as these systems have not been commonly used for their sensitivity towards the extremely cold climate. A detailed monitoring system was installed in the house. It enables the evaluation of the indoor air quality, as well as building's energy performance.

The aim of this investigation was to evaluate the performance of the newly constructed house by and compare it with the performance of identical house built in a traditional way by using a computer model. The data obtained from the measurements in the new house were used to verify the model.

Significant energy savings and improvements of indoor air quality were found in the new house when compared to the traditional one. Moreover, all the extra measures have a feasible payback time despite high prices of labor and transportation to Greenland.

INTRODUCTION

Until recently, little attention was paid to the energy efficiency of the buildings constructed in Greenland. This coupled with extreme climatic conditions (very low temperatures over long periods of time, lack of sun in the winter period and strong winds) results in high energy consumption for heating (Vladyková et al. 2011). Additionally, the buildings are usually poorly ventilated, what results in a poor indoor air quality (IAQ), mould growth and greater exposure to indoor air pollutants. Assuming that people in Greenland spend a significant part of the long winters indoors, the risk of health problems due to poor IAQ is considerable.

The first step to minimize heat losses from buildings in the Arctic is to optimize the building shape and amount of insulation (Vladyková and Rode 2011). Additionally, the air tightness of the building envelope has to be ensured, together with the utilization of solar heat gains. Also, heat recovery from the exhaust air should be used. However, more difficult than decreasing the annual heating demand is in fact lowering the peak heat load of the building. It is due to the combination of very low temperatures with no solar gain on the design days. Vladyková

and Rode (2011) concluded that fulfilling the requirement of maximum 10 W/m^2 of peak demand required for the building to fulfil the passive house requirements (Passive House Institute 2007), would require the use of economically unreasonable technical solutions.

Mechanical ventilation systems besides allowing heat recovery from the exhaust air also permit for better control of the air change and control of indoor air parameters, e.g. humidity or CO_2 concentration. For Arctic dwellings, 20% relative humidity (RH) during winter is considered optimum. If the value drops below this point, discomfort perceived by the occupants increases significantly. The risk for condensation and consequent mould growth is increasing at RH above 20%, what consequently leads to the indoor air quality decrease and may affect residents' health (Ninomura and Bhargava 1995). During cold periods there is a high risk of frosting of the heat exchanger when the humid exhaust air stream is cooled below its dew point and moisture condensation on the surface below the freezing temperature occurs (Bilodeau et al. 1999). This issue has to be taken into account when designing the system.

Apart from improved IAQ, using mechanical ventilation can be economically justified thanks to energy savings due to heat recovery. A study of buildings constructed in Kotzebue, Alaska showed simple payback time (SPBT) of mechanical ventilation of 7 years (Ninomura and Bhargava 1995). Since 1995 (when the research was performed) the energy prices have increased and technology became cheaper, therefore, the SPBT for similar investment nowadays would be even shorter.

Aim of the study

The aim of this investigation was to compare the performance of the newly constructed energy-efficient single family house with the performance of a standard house of the same kind in Arctic conditions by means of computer simulation.

METHODS

Description of the building

The investigated building is a 122.2 m^2 single family house located in Akia neighbourhood in Sisimiut, Greenland. The building was constructed as wooden house typical for Greenland. However, in comparison to standard type houses, several improvements were implemented. The thermal insulation in external walls and ceiling below the loft was made significantly thicker ($U_{\text{ext.wall}} = 0.14 \text{ W}/(\text{m}^2 \cdot \text{K})$ in comparison to $U_{\text{ext.wall}} = 0.20 \text{ W}/(\text{m}^2 \cdot \text{K})$ required by Greenlandic Building Regulations (2006), $U_{\text{ceil.bel.loft}} = 0.093 \text{ W}/(\text{m}^2 \cdot \text{K})$ in comparison to $U_{\text{ceil.bel.loft}} = 0.15 \text{ W}/(\text{m}^2 \cdot \text{K})$). Additionally, a mechanical ventilation system with rotary heat exchanger was installed in the building. The windows in the building are triple-glazed. The layout of the building is presented in Figure 1.

Description of the building models used for the simulations

The simulation of building operation was made in IDA ICE 4.6.2 and the weather file used was Test Reference Year (TRY) for Sisimiut. The setpoint temperatures during the heating season were set according to the setpoints used by the occupants. The temperature setpoints are presented in Table 1. The design power of the floor heating was assumed to be the same in all rooms where heating floor was located and calculated as 30 W/m^2 . The thermal bridges were set as "Good" in IDA ICE setup. The leakage of the building envelope was set to 3 h^{-1} at 50 Pa over- and underpressure, value similar to 3.2 h^{-1} measured in the Low Energy House in Sisimiut, Greenland (Rode et al. 2009).

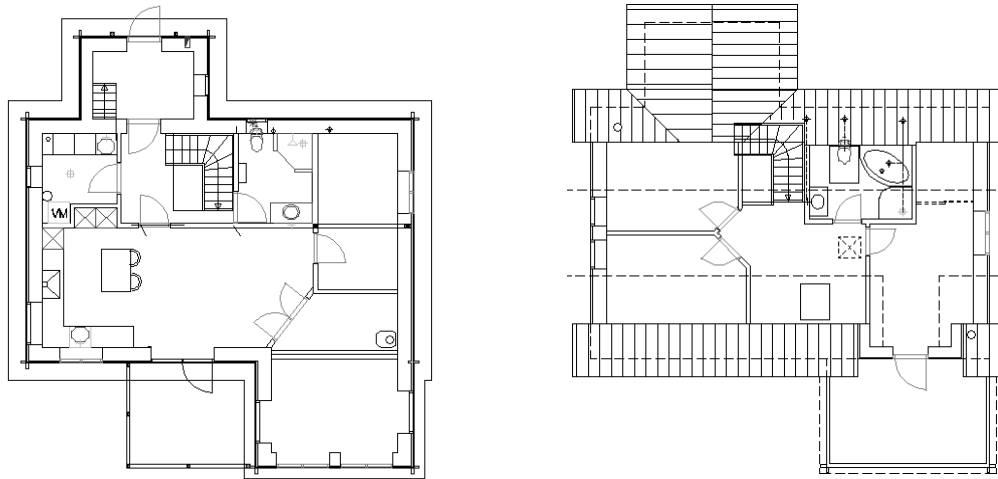


Figure 1. - Layout of the building, left - ground floor, right - first floor

Table 1.-Setpoint temperatures

Room	Temperature setpoint day [°C]	Temperature setpoint night [°C]	Night period
Entrance	11,5	11,5	Weekdays: from 23:00 to 6:00 and from 9:30 to 16:00 Weekends: from 23:00 to 7:00
Hall downstairs	19,5	17,0	
Hall upstairs	20,0	17,0	
Kitchen and dining room	21,5	20,0	
Living room	21,0	20,0	
Office (downstairs)	20,5	18,5	
Bedrooms	19,5	18,5	
Bathrooms	21,0	19,5	

The ventilation system was set to supply 7 l/s to the living room and all the bedrooms, excluding the master bedroom upstairs (where 14 l/s are supplied). The air is extracted from the bathrooms (10.5 l/s), from the kitchen (14 l/s) and from the utility room (7 l/s). The air flows are balanced and result in an air change rate (ACH) 0.57 h^{-1} . Currently, there is no heater installed in the ventilation unit, so supply air is heated up only by means of heat recovery from the exhaust air. The efficiency of heat exchanger was set to 75% (according to technical documentation the temperature efficiency of the exchanger is up to 80% (Swegon 2014)). If the return temperature exceeds $23.5 \text{ }^\circ\text{C}$, the rotor stops to prevent overheating. The dead band of the thermostat controlling the bypass use was set to 1 K. Internal heat gains were modelled as 5 W/m^2 in average, with separate schedules used for occupants in the main part of the house, occupants in the bedrooms and lights and equipment. It was assumed that no significant gains from the occupants occur in entrance, utility room, hall (both downstairs and upstairs) and two bedrooms upstairs, as they are not in use at the moment. Heat gains from both bathrooms were considered as negligible (Molinet al. 2011). The schedules used were based on the heating setpoint schedules and are presented in Table 2.

The heat gains from the two occupants equal to 213.8 W - the other heat gains were adjusted to keep the average heat gains in the building at 5 W/m^2 , what results in 9.2 W/m^2 heat gains from the lights and equipment during the ON hours.

Table 2.- Schedules used in the model

Heat gains schedule	"ON" hours
Occupants - most of the house	06:00 - 09:30 and 16:00 - 23:00 on weekdays 07:00 - 23:00 during weekends
Occupants - bedroom	23:00 - 06:00 on weekdays 23:00 - 07:00 during weekends
Lights and equipment	06:00 - 09:30 and 16:00 - 23:00 on weekdays 07:00 - 23:00 during weekends

To prevent overheating, window opening was implemented in the models. It was assumed that the windows open by 10% if the temperature in the zone exceeds a cooling setpoint of 23.5 °C (25.5°C for bathrooms). Only one window in each zone was assumed to open, with the exception of the living room, where two windows had to be open to prevent overheating. As the schedule was supposed to simulate occupants' behaviour, it was assumed that the windows can be opened only during the day (between 7:00 and 23:00). However, as overheating risk was related to excessive solar heat gains, this limitation does not increase the risk of overheating. It was expected that the ventilation unit is going to operate even if the windows are open, as in the installed system there is no possibility of automatically regulating the air flow into individual rooms.

To compare the performance of the new house with a house constructed using standard solutions (including double-glazed windows), additional model was created. It was assumed that the supply and return air for all the rooms will remain the same as in the base model. However, the heat recovery efficiency was set to 0% as typically the ventilation would be natural instead of mechanical. Floor heating was replaced with radiators. The temperature setpoints and internal heat gains remained the same as for the base model.

To simplify addressing of the results from the different models, the below presented convention was used:

- Model 0 - model of the existing house with the building monitoring system installed.
- Model ST - model of the building with wall U-values as required by the Greenlandic Building Regulations, the ventilation rates in all the rooms were assumed to be the same as in Model 0, no heat recovery was modelled, heating system with radiators.

Model validation

To validate the model, the results obtained from simulation were compared with the measurements using Wilcoxon Signed-Ranks Test (Zaiontz 2014). For the simulation, a weather file with actual temperatures measured during the test period was used. Subsequently, the simulated energy consumption was compared with the measured one. Only periods, when no domestic hot water was used for over 6 hours were taken into account, to eliminate the influence of the DHW consumption on the measured oil consumption. Additionally, mean and median energy delivered in the investigated periods were compared.

Economic evaluation

To evaluate the economic profitability of the of the extra insulation and ventilation unit pay-back time (PBT) was calculated. Three cases were investigated - for the oil price remaining at the current level of 6.41 DKK, increasing at an average rate of 3.68% (the same as between 2000 and 2012) (INI 2012) and increasing at the average rate of 5%. The inflation rate was assumed to be 2%.

RESULTS

Model validation

The z-value calculated for the sample of 241 periods was 1.78 and the p-value was equal to 0.07. Thus, as the selected level of significance $\alpha=5\%$, the simulated and measured results were not significantly different and the model was validated. The mean and median heating power for the model and existing building were: $\bar{E}_{real}= 2781.4 \text{ W}$, $\bar{E}_{sim} = 2519.7 \text{ W}$, $\mu_{Ereal}= 2646.0 \text{ W}$, $\mu_{Esim}= 2539.9 \text{ W}$. Total energy delivered for the model in the investigated periods was 607.24 kWh, while for the existing building it was 670.32 kWh.

Energy consumption for space heating

For Model 0 with window opening the space heating peak load was 13.81 kW and for model ST with window opening - 14.74 kW. The annual energy demand for heating and ventilation for model 0 was 11863 kWh, what gives 97 kWh/m² of the heated area, and for the ST model - 21626 kWh, what corresponds to 177 kWh/m². The significant peak load is caused by the increase in the energy demand during the hours, when the heating setpoint increases. Space heating duration curves for models 0 and ST are shown in Figure 2.

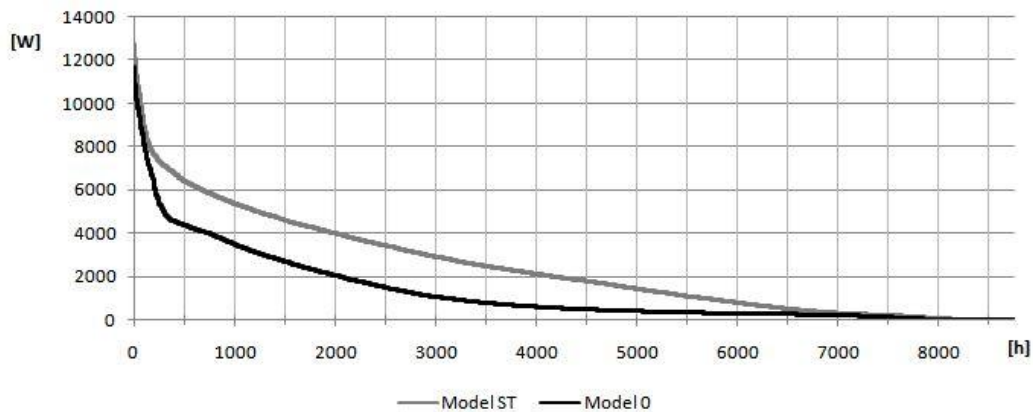


Figure 2 - Heating load duration curves for model 0 and model ST

A significant part of energy savings comes from the energy recovered in the heat exchanger - 6854 kWh during one year. During the coldest months (December - March) the power of heat exchanger is around 1000 W. The energy recovered in the ventilation system is shown in Figure 3.

The initial results for the model without window opening implemented show that there is a serious risk of overheating in the rooms with large share of a window surface, that cannot be mitigated by ventilation only, both in the model 0 and ST. Figure 4 shows the mean air temperatures in the living room (critical room for overheating due to the large window surface) in the two models analyzed.

The overheating problems start already at the end of February for both models. The maximum temperature recorded in the living room in model 0 is lower than in model ST (40.5 °C compared to 42.6 °C). In model 0 temperature in the night often drops less than in the another model and doesn't reach 21 °C, so the heating system does not turn on during the night, what is the case in model ST. It is due to the lower U-value of the building envelope in model 0, as the building mass for both cases is similar and cannot be a decisive factor.

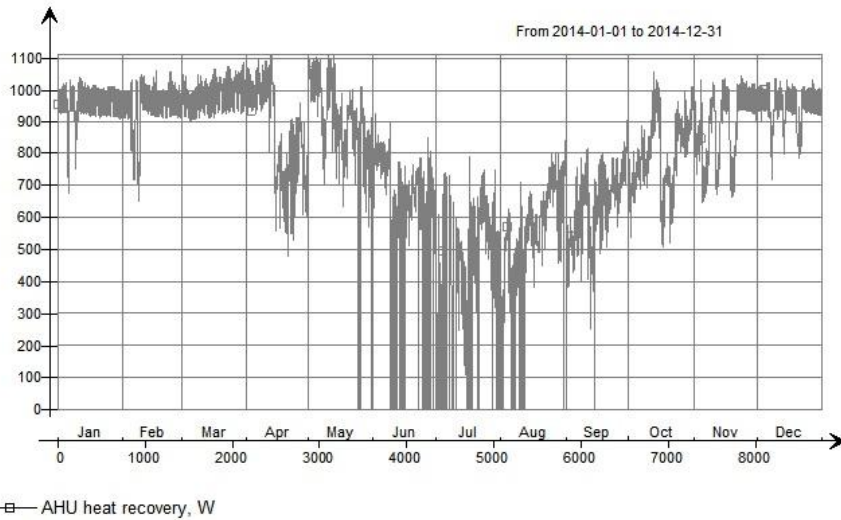


Figure 3 - Energy recovered in air handling unit

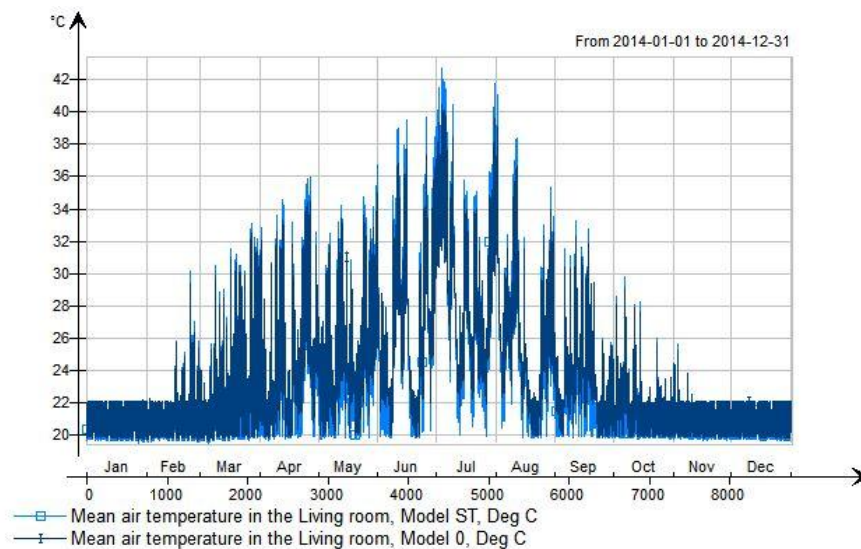


Figure 4 - Temperatures in the living room in model 0 and model ST during the whole year

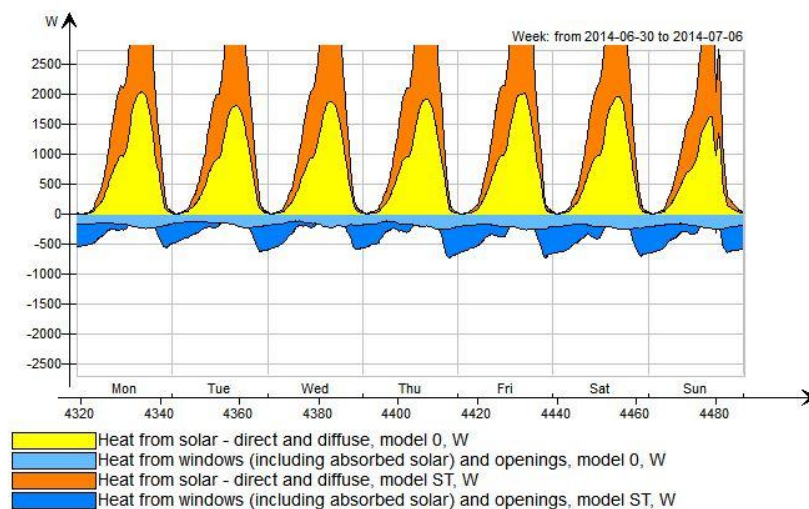


Figure 5 - Heat balance of solar heat gains and heat from windows during the week with highest temperatures in the living room 30.06 - 06.07 for models 0 and ST

The lower recorded maximum temperatures in the living room for model 0 are related to the difference between the window parameters in both models, as the solar heat gains for the model 0 were lower than in the ST models (Figure 5). It is due to the lower radiation transmittance of the windows in model 0 compared to model ST.

Occupants' perception of the indoor climate

Due to the fact that investigated building is a single family house, no formalized survey was made, as the results would not be statistically significant. However, the occupants were interviewed about their satisfaction with the indoor climate and indoor air quality.

No problems with discomfort caused by draft or cold air influx into the rooms were reported. There were also no problems with excessive or insufficient humidity of the air inside the building - the occupants did not experience dryness or irritation in the eyes, nose or skin, the air did not feel too humid and no problems related to too high humidity were observed. The only problem mentioned was related to the temperature in the dining room increasing too high during the sunny days, even when the outside temperatures are low (around -15 °C), what corresponds with the results from the initial simulations.

Economic evaluation

For the oil prices at the current level, the calculated predicted payback time is 18 years and 74 days, for the prices rising annually by 3.68% - 13 years and 315 days, and for the prices rising annually by 5% - 12 years and 332 days.

DISCUSSION

The space heating energy consumption for the model 0 is about 55% of that of model ST - the amount of the energy saved corresponds roughly to 1100l of heating oil saved each year. The maximum heat demand is very similar in both buildings, what corresponds with the results obtained by Vladyková and Rode (2011). Based on the duration curves it can be noticed, however, that the peak demand in model 0 lasts significantly shorter than in model ST - the demand exceeding 5000 W occurs for 296 h, while in the ST model - for 1223 h. Simulated annual energy consumption for space heating of 97 kWh/m² is lower than 140 kWh/m² measured in low energy house (Rode et al. 2009) and 150 kWh/m² calculated for the Apisseq dormitory (Vladyková and Rode2011). However, it is still higher than 80 kWh/m², that was the goal value for low energy house (Rode et al. 2009).

Heat recovered by the heat exchanger constitutes a large part of the difference between the heat demand in model 0 and model ST - for a big part of the cold season the heat recovered is around 1000 W. For the entire year it corresponds to 56,1 kWh/m². It confirms the importance of using ventilation system with heat recovery if the building energy consumption is to be lowered without sacrificing the IAQ. Simulated energy recovered is thus higher than 27,3 kWh/m² given by Vladyková and Rode (2011) for the Apisseq dormitory. The assumption that the ventilation unit is going to operate even if the windows are open ensures also that there is no risk that occupants would not turn the unit back on after closing the windows. Despite the concerns about heat exchanger frosting, no such problems were reported by the occupants in winter 2014/2015 even at outdoor temperatures of -30 °C.

Furthermore, the results show that even in averagely insulated buildings in the rooms with large window surface a significant risk of overheating occurs for a long period - even in the arctic climate. Additionally, due to low angle of the sun, typical external shading solutions

used in temperate climates, such as overhangs over windows, are not very effective. Vladyková and Rode (2011) suggest the installation of vertical shadings to minimize the risk of overheating and glare from the low angle sun in the summer. As overheating occurs due to the solar heat gains, the temperature may rise drastically in one part of the building, while in the other there is still a need for heating. In the analyzed results that is the case e.g. for the living room and the bedroom upstairs on the side of the building entrance.

CONCLUSIONS

Increasing the insulation layer and using the mechanical ventilation system with heat recovery allows to decrease the energy consumption for space heating by about 45%. However, the design heat load in the energy-efficient building is only slightly lower than in the standard one. Significant part of the reduced energy consumption comes from the heat recovered in the ventilation system. The investments are also economically justified, especially taking into account the uncertainties concerning future oil prices in Greenland. In both models there is a risk of overheating. In residential buildings it can be mitigated by opening the windows, but in buildings where it is not possible additional counter-measures should be taken.

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