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The potential for energy efficient building design - differences between Europe and the Arctic

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The potential for energy efficient building design - differences between Europe and the Arctic

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SUMMARY:
The design of a highly energy efficient building is closely connected to the climate conditions. The article deals with the way of designing buildings for the Arctic where very often the knowledge and experiences from European conditions are adopted. The aim is to investigate which design parameters can be adopted in the Arctic, what needs to be altered to reach an energy efficient building, and what is the sensitivity of various design parameters to the potential on energy savings.

A new and energy efficient dormitory called "Apisseq" has been constructed in the town of Sisimiut, Greenland, as an ambitious project which will focus on minimal energy consumption. This will be documented using an extensive monitoring system with energy meters, indoor climate sensors and sensors built-in to constructions. The model of a dormitory is used for the investigation of key parameters that could decrease the energy demand, and inspiration and comparison are made with a passive house model such as a passive house Kranichstein in Darmstadt, Germany. Several investigations are performed: the necessity of air-tight constructions which are free of thermal bridges and the potential to use gains from sun that shines at shallow angles. Furthermore, the investigation of optimized energy consumption is analyzed in order to reach the most suitable solution for energy efficient building for Arctic climate.

1. Introduction

The design of buildings in the Arctic Greenland is influenced by the climate characteristics, availability of building materials, and knowledge of building technologies and techniques. The natural resources are very scarce in Greenland and everything must be imported and delivered to the building site by ship or plane due to the long distances and no roads. The Greenlandic Building Regulations are derived from the Danish Building Regulations and applied with a delay of some years and not entirely taking into account the climatic differences between Greenland and Germany. For building of energy efficient buildings it is essential that skilled labour is employed but the education in energy efficient building technologies is not widespread in Arctic countries. For the region north of the Polar Circle, the current Greenlandic Building Regulations (GBR 2006) stipulates a maximum annual consumption of energy for heating of 185 kWh/(m^2·a) or requirements on maximum U-values for walls, doors and windows as in TABLE 2, and a maximum window/floor area of 22%.

When designing the energy efficient buildings for the Arctic it is obvious that conditions regarding outdoor temperature, solar pattern, local building techniques and user habits must be considered. The weather in Sisimiut, Greenland (latitude 66.6°N, longitude 53.4°E), is quite different from Darmstadt, Germany (latitude 49.5°N, longitude 8.4°E). The heating degree hours using the PHPP formula with T_{base} = 16°C for Sisimiut are 146.3 kKh/a compared to 79.8 kKh/a in Darmstadt. The monthly average temperatures varies between from -14.0°C to 6.3°C in Sisimiut while for Darmstadt the variation is from 0.7°C to 18.9°C. Roughly, Sisimiut can be regarding as being "twice as cold" as Darmstadt. The global solar radiation on a horizontal surface is for Sisimiut 841 kWh/(m^2·a) and for Darmstadt it is 1,038 kWh/(m^2·a), but the difference is in the angular distribution of solar radiation in the Arctic. In

Sisimiut there are days in winter where the sun doesn't dawn, while he summer has days where the sun doesn't set. In the Arctic, there is less radiation on a horizontal surface, but significantly more radiation on vertical surfaces because of the shallow solar angle (TABLE 1). This facilitates good possibilities for passive solar gains through (vertical) windows in Arctic buildings in other seasons than the winter.

TABLE 1. Solar radiation on a horizontal surface

	Solar radiation on a horizontal surface [kWh/(m²·a)]			
	South	East	West	North
Darmstadt	949	652	653	362
Sisimiut	1,019	815	839	442

One examples of an energy efficient houses built in the Arctic is the Low-energy house in Sisimiut (Norling, 2006), which is a residential house for two families with floor area of 208 m^2 and targeted energy consumption 80 kWh/(m^2·a) for heating. The Low-energy house is an advanced building made of a well-insulated building envelope, which is virtually free of cold bridges, has high performing windows, and a ventilation system with a counter-flow heat recovery unit. The building uses solar and other passive gains to achieve energy efficiency, and the auxiliary heat comes from an oil boiler. Experiences from the Low-energy house have been used as inspiration for making the new dormitory.

2. New dormitory Apisseq

The dormitory "Apisseq" (which means "polar bear's pit") was inaugurated in November 2010. The energy monitoring of the dormitory starts in the beginning of 2011. The new dormitory has a gross heated floor area of 1,435 m^2 (A_{gross}) and accommodates 40 students, mainly in single-room apartments but also with a few three-room apartments (treated floor area is A_{TFA} = 1,134 m^2, and the gross volume of the building is V_{gross} = 4,382 m^3). The building consists of three quarters of a ring that circumfuse a protected courtyard (FIG 1). In the centre of the building, facing the inner courtyard is a glazed atrium which contains a main staircase and common facilities. Access to the apartments is from canopied balconies made from a suspended steel structure, which also faces the courtyard.

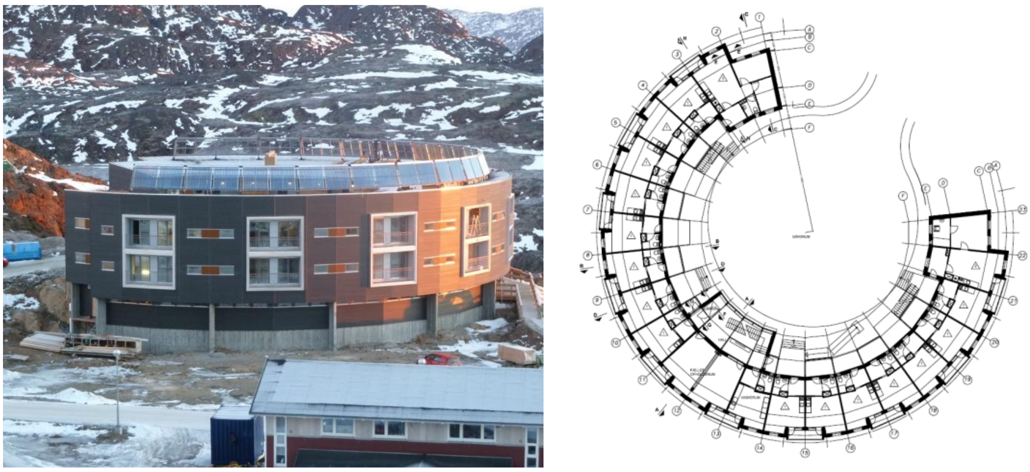

FIG 1. Dormitory Apisseq in Sisimiut, Greenland

The building has a load bearing structure of inner concrete walls and floors. The external walls are lightweight insulating constructions made from vertical wooden I-beams of 150 mm and mineral wool in between, which are fastened so they pass on the outside of the concrete structure. Furthermore, the exterior walls have on the inside 2 x 70 mm of insulation. On the exterior wall 9 mm gypsum is placed as wind breaking layer behind a ventilated cavity and on the interior side is the vapour air tight barrier.

The external floor of insulated building's envelope is made from 50 mm of mineral wool and below is space for unventilated space for horizontal installation with another 100 mm mineral wool insulation. The ceiling to the cold attic is made from 2 layers of 150 mm of insulation lying on the top of concrete ceiling of 180 mm. The windows are 2 layers glazing with U-value 1.1 W/(m^2·K), with "warm edge" frames supplemented with third removable glass layer from inside. The exterior doors have the U-value of 1.8 W/(m^2·K).

TABLE 2. Calculated U-values of different constructions compared to GBR 2006 (GBR 2006)

Construction	Insulation thickness [mm]	U-value calculated [W/(m^2·K)]	U-value demand [W/(m^2·K)]
Floor	50+100	0.13	0.15
Wall	290	0.15	0.20
Roof	2*150 mm	0.13	0.15

The building's heating is delivered by a floor heating system, by radiators, and by ventilation which is provided with a heat recovery system. Solar energy contributes to heating the domestic hot water as well as partly to the room heating. The rest of the heating is provided from the town's district heating system. The ventilation system supplies the building with fresh air and for exhausting the used air, and the heat is recovered with an efficiency of 75%. An after-heater ensures the supply air has a temperature of at least 18°C.

2.1 Energy demand

The annual heat loss is calculated to be approximately 150 kWh/(m^2·a) based on the Danish Standard DS 418 (DS, 418) for calculating design heat loss and the heating degree days. Hot water consumption is calculated to be approximately 80,000 kWh/a, or 52 kWh/(m^2·a). Annual production of solar energy is calculated to be 400 kWh per m^2 of the solar collector, or 40 MWh/a for the whole dormitory.

2.2 Monitoring system

A monitoring system is set up to continuously log the energy consumption, indoor climate, moisture in constructions, and the meteorological situation. A LonBOX system gathers the data about the building performance. A total of 9 Kamstrup energy meters are installed to measure the following: production of solar energy, energy transported from solar collectors to storage tanks and from the tanks to the domestic hot water system, hot water consumption, circulation heat loss, hot water contribution to heating, district heating contribution and energy delivered from tanks to heating, and total heating consumption. Honeywell sensors were chosen for registering the indoor climate (combined sensors for temperature and relative humidity) together with Vaisala CO_2 sensors to log the concentration in 5 selected single living units. A total of 15 Vaisala sensors are built-in to monitor the temperature and relative humidity at various places in the constructions. For meteorological measurements, a sunshine pyranometer is installed on the roof.

3. Methodology

The methodology of investigation is based on comparing two models: a model for the passive house "Kranichstein" located in Darmstadt, Germany, and a model "Apisseq" for the dormitory located in Sisimiut, Greenland. The Kranichstein house was built in 1991 and is an example of a super-insulated, airtight house that utilises solar and internal gains so that only a very small amount of space heating is necessary, i.e. space heating demand of 15 kWh/(m^2·a) when located in Darmstadt, Germany. That small amount of heating is supplied to the fresh air through the ventilation system with heat recovery, where the target for a passive house is to have a heating load that does not exceed 10 W/m^2 per treated floor area (A_{TFA}).

The passive house Kranichstein and the dormitory Apisseq are used in a sensitivity analysis of separate parts of the dormitory's building envelope to investigate if it could be enhanced to reach up to the passive house standard. The following is comprised in the analysis: level of insulation, thermal bridges, air tightness and heat exchanger efficiency. Each parameter is improved to reach the equivalent effect as a passive house in the Arctic, and the potential energy savings is noted. Since the windows have influence on the heat loss, and at the same time contribute solar gains, the investigation of solar radiation potential is made for two geographical locations with different solar patterns: Darmstadt and Sisimiut. The task is to identify important design characteristics in the building design as key figures in the design. An optimized solution for an energy efficient building in the Arctic is proposed.

4. Results

4.1 Annual space heating demand

The building´s characteristics are important design factors including the amount of insulation, air tightness of the building envelope, performance of windows, and the ventilation and heating systems. As the insulation is one of the main parameters in the building design, the amount of insulation is investigated using the annual energy balance. Insulation thickness in the thermal bridge free construction is an important factor concerning the heating demand of the building. The amount of insulation necessary to reach a passive house requirement of annual space heating demand of 15 kWh/(m^2·a) is investigated using the annual energy balance with the distribution of gains and losses (FIG 2).

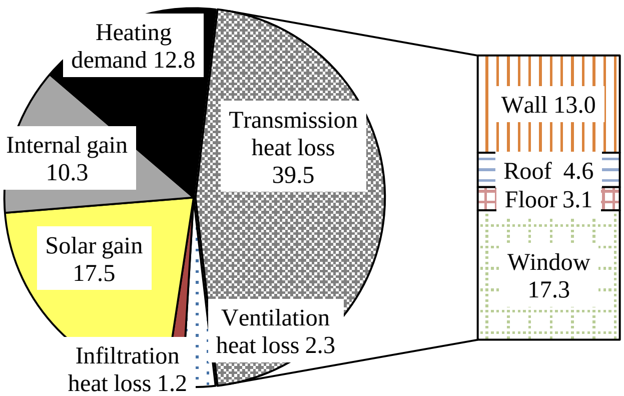

FIG 2. Energy balance in kWh/(m^2·a) with distribution of gains and losses of a passive house Kranichstein in Darmstadt

An example for the external wall is shown in FIG 3, where for a passive house in Darmstadt, the transmission heat loss through the insulated building wall equals to 13.0 kWh/(m^2·a) with U_{wall} = 0.138 W/(m^2·K). If the Kranichstein house were located in Sisimiut and should obtain a transmission heat loss for the wall of 13.0 kWh/(m^2·a), the wall U-value would need to be as low as 0.075 W/(m^2·K). Due to the larger surface area of the building envelope, the equivalent U-value to reach a passive house standard for the Apisseq dormitory in Sisimiut would be 0.067 W/(m^2·K). TABLE 3 shows the same methodology applied to other of the building's components and systems. The energy savings for Apisseq show that the biggest potential to save the energy lies in minimizing the heat loss through the building's envelope, and improving the wall's characteristics is most beneficial.

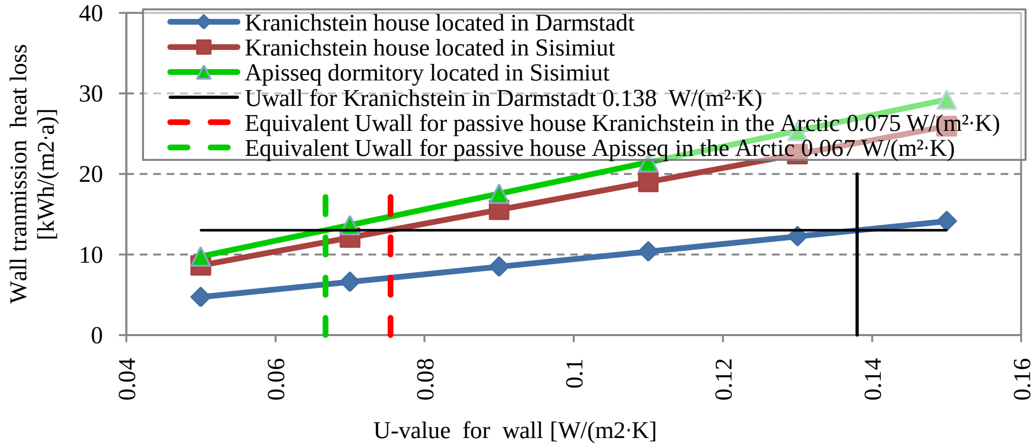

FIG 3. Level of insulation for Apisseq compared to level of insulation for Kranichstein, and equivalent effects with values for locations in Darmstadt and Sisimiut

TABLE 3. Equivalents for improvement to a passive house standard and energy improvements for Apisseq from current state to passive house standards

State	Current state		Passive house		Energy improvements for Apisseq [kWh/(m^2·a)]
Location	Kranichstein Darmstadt	Apisseq Sisimiut	Kranichstein Sisimiut	Apisseq Sisimiut	
U_{wall}[W/(m^2·K)]	0.138	0.150	0.075	0.068	12.8
U_{floor} [W/(m^2·K)]	0.131	0.130	0.041	0.038	6.1
U_{roof} [W/(m^2·K)]	0.108	0.130	0.069	0.059	4.8
$\psi_{window,/foundation}$ [W/(m·K)]	0.010	0.03/0.25	0.010	0.010	4.5
Air tightness [h^{-1}]	0.022	0.135	0.022	0.012	3.0
Heat exchanger [%]	80	75	90	90	4.1

The windows must have the best thermal performance, i.e. the lowest possible thermal heat transfer (U-value), but at the same time be able to obtain the highest amount of solar radiation, i.e. the window area should be optimal in size and orientation regarding transmission loss and solar heat gain. In the current situation, the balcony windows/doors are embedded in the façade in Apisseq with orientation of 22° distributed over various orientations on the façade of the circular building, and they contribute to the energy balance with 7,600 kWh/a of solar gains, and at the same time they have a total transmission heat loss of approximately 32,800 kWh/a with U_{window} = 1.1 W/(m^2·K) and g-value = 0.56 with a shading factor F_s of 0.56. FIG 4 illustrates the utilization of solar gains obtained from embedded window/door in balconies and other windows in a passive house Kranichstein located in Darmstadt and compare it to different levels of improved windows in Apisseq in Sisimiut for all window orientations.

For the selection of windows it would be desirable to obtain the same amount of solar gain as what is lost by transmission through the windows. Full compensation of the transmission heat loss through windows can be done only in the European locations with current technologies, e.g. the transmission heat loss through a window with U_{window} = 0.78 W/(m^2·K) in Darmstadt can be covered by using a glass with g-value 0.45-0.65 for south oriented windows. To cover fully the transmission heat loss in Sisimiut, i.e. to have a positive net energy gain, a super window with $U_{window} \leq$ 0.44 W/(m^2·K) with g-value ≥ 0.57 would have to be used for the south orientation (for west and east orientation the g-value should be ≥ 0.95) and higher. The embedded balconies in Apisseq shade the solar gain with the resulting shading factor 0.56 while the windows on the outer façade have a shading factor F_s of 0.9.

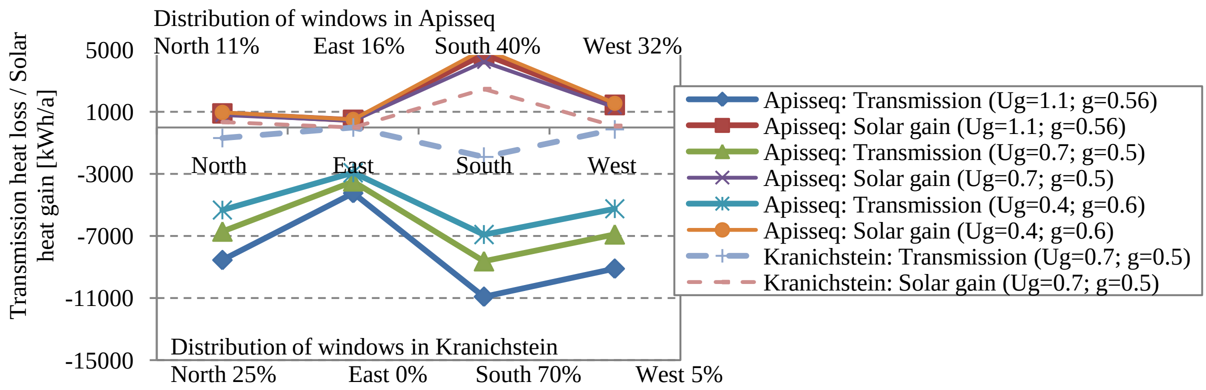

FIG 4. Comparison of solar heat gains and transmission losses of the passive house Kranichstein in Darmstadt with similar values for the windows of the Apisseq dormitory in Sisimiut analyzing different scenarios for $U_{glazing}$ and g-value

The internal gain is calculated with 2.1 W/m^2 and for a Kranichstein it equals to 10.3 kWh/(m^2·a). The national standard for Greenland prescribes use of an internal gain of 5.0 W/m^2 and for Apisseq it equals to 24.5 kWh/(m^2·a). If the value 5.0 W/m^2 is used, the calculated annual internal gains can almost cover the missing solar gains.

4.2 Heating load

A passive house utilizes solar and other passive gain in the super insulated and airtight buildings so the heat peak heating load of the building is 10 W/m^2. The design heat load in a passive house is calculated for the two special days: “Day 1” - a cold day with clear sky and “Day 2” - a moderately cold day with overcast sky. On such two design days there would be significant or moderate solar radiation in a European location, but in an Arctic location such days would have no solar radiation and could be represented as one day. Therefore the heating load has to be covered only by the internal gain, which in a passive house equals just 1.6 W/m^2 to represent the worst case situation when nobody is present in the house. FIG 5 shows the proportion of heat loss and gains when calculating the heat load and showing the contribution of different parameters.

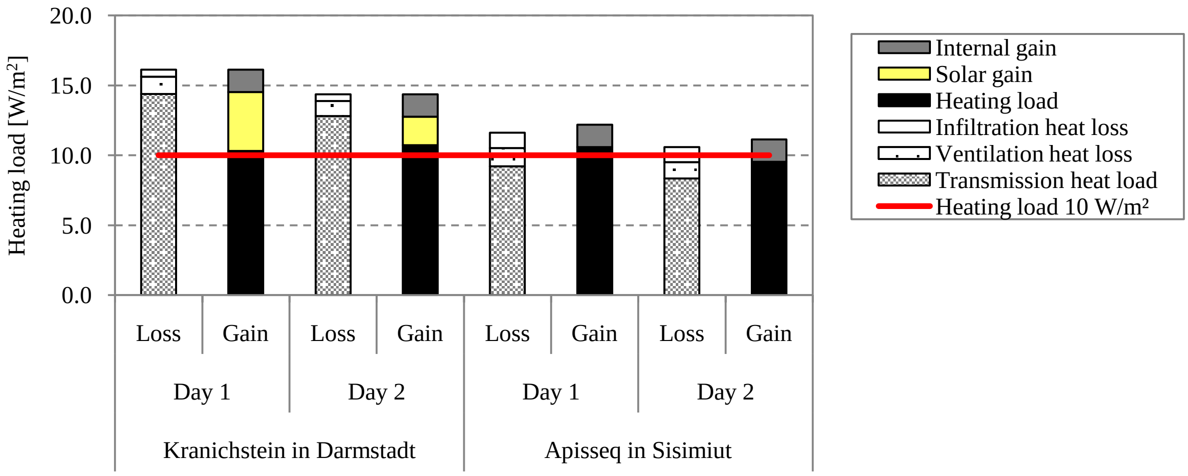

FIG 5. Distribution of losses and gains for calculation of peak heating loads for the houses located in Darmstadt or Sisimiut

In the Arctic location, in order to reach a heating load as low as 10 W/m^2 on a design day without solar radiation, the transmission heat loss through the building envelope has the major impact. The most significant building parts are the windows and walls. An unrealistically well insulating window with U_{window} = 0.492 kWh/(m^2·a) with shading factor F_s = 0.56 would have to be used due to the current building design with embedded windows in balconies or heat mirror windows together with the insulation thickness of 550 mm with thermal conductivity λ = 0.025 W/(m·K) or with traditional mineral wool insulation with λ = 0.037 W/(m·K) and insulation thickness of 900 mm.

TABLE 4. Building characteristics needed in order to reach a passive house standard of heating load 10 W/m^2

	Kranichstein in Darmstadt		Apisseq in Sisimiut	
	Day 1	Day 2	Day 1	Day 2
Design temperature [°C]	-11.4	-7.5	-32.2	-26.9
Solar gain (North, East, South, West) [W/m^2]	11, 35, 90, 35	15, 20, 40, 25	0, 0, 0, 0	0, 0, 0, 0
U_{wall} [W/(m^2·K)]	0.138		0.042	
U_{roof} [W/(m^2·K)]	0.108		0.035	
U_{floor} [W/(m^2·K)]	0.131		0.035	
U_{window} [W/(m^2·K)]	0.777		0.492	
Infiltration [h^{-1}]	0.019		0.030	
Heat exchanger efficiency [%]	80		91	

4.3 Optimized energy design and consumption

FIG 6 gives an insight into the current situation presenting the energy balances for a typical Greenlandic house, “Illorput” located in Sisimiut (Kragh, 2004) and the Apisseq dormitory, compared to a passive house (located in Darmstadt, Germany). Typical new residential buildings in Sisimiut have only the insulation levels required by GBR 2006 and are usually not equipped with a ventilation system with heat recovery. Heating is provided by an oil-boiler, ventilation is secured by venting and exhausts fans in kitchen and bathroom, and the air tightness of the envelope is probably not very good. The passive house model of Kranichstein has a super insulated and very air tight building envelope, and the ventilation heat loss is reduced by efficient heat recovery system. The initial calculation of the energy efficient dormitory Apisseq shows that there is a potential for improvement if the building is made more air tight and the amount of insulation is increased. The annual space heating demand for a typical house is 230 kWh/(m^2·a) (GBR, 2006), for a passive house 15 kWh/(m^2·a) and for the dormitory Apisseq 150 kWh/(m^2·a).

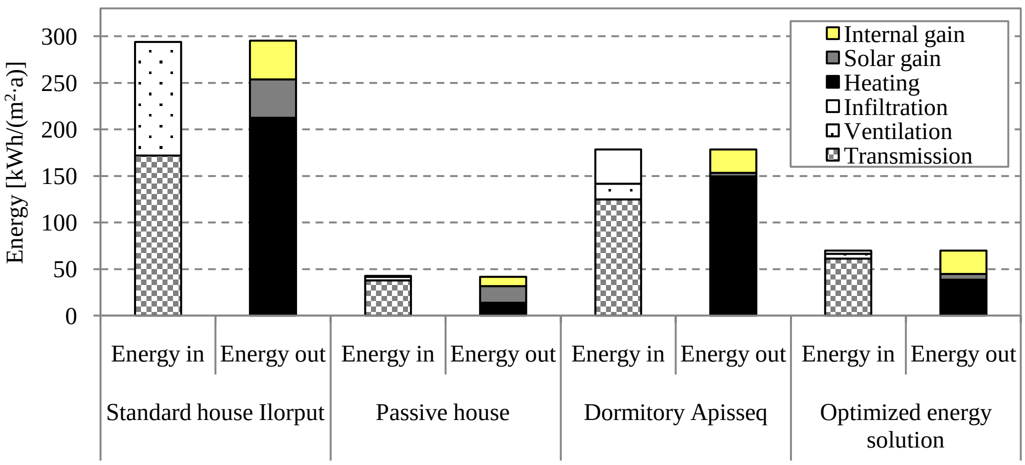

FIG 6. Energy balance for a typical residential house, a new dormitory Apisseq and a passive house compared to an optimized energy solutions for the Arctic

The Apisseq investigations show that the largest potential lies in improvement of the building envelope. The question is to what limit the improvement of the building envelope should go. The optimized building solution from Section 4.2 would reach an annual heating demand 40 kWh/(m^2·a) that would require the ventilation 90% with air change rate 0.3 h^{-1} (improvement of 12 kWh/(m^2·a) from the current state), improved air tightness 0.135 h^{-1} to 0.021 h^{-1} (improvement by 33 kWh/(m^2·a)), improved windows moved to the outer surface of the façade with U_{window} = 0.8 W/(m^2·K) and g = 0.6 and U_{door} = 0.8 W/(m^2·K) (improvement by 2 kWh//(m^2·a)), and improved insulation properties to U_{wall} = 0.07 W/(m^2·K), U_{floor} and U_{roof} = 0.08 W/(m^2·K).

5. Discussion

The first step when building in the Arctic is to minimize the heat loss with the most optimal use of a building shape and insulation level. Often the cost of insulation governs the decision of what amount of insulation will be used rather than making decisions from a broader angle. For example, a passive house offers more energy savings when using more insulation. The calculations show that the calculation of energy balance with annual method to fulfil the space heating demand of 15 kWh/(m^2·a) can be accomplished in the arctic city Sisimiut in Greenland. But the peak heat load of no more than 10 W/m^2 is more difficult to achieve on the design days as there is no solar gain, and therefore there will have to be used unrealistically high amounts of insulation to achieve it.

The investigations show that it is possible in the Arctic to fully cover the annual transmission heat loss with solar gains obtained from solar radiation only with very efficient windows that are not on the market yet. The most beneficial orientations for windows are also in Sisimiut that they are facing south, east and west. The dormitory building investigated in the paper has windows which are embedded behind balconies and in windows recesses. Putting the windows to the front of the facades would enhance the solar gains, but on the other hand the window's characteristics would be affected by high storms and the transmission heat loss would increase. Also the vertical shadings have to be installed to minimizing the risk of overheating and glare in the summer from the low angle sun.

6. Conclusion

A solution for a passive house may depend on the choice if one should focus on reaching the specified space heating demand of 15 kWh/(m^2·a), or the demand that the peak heat load must not exceed 10 W/m^2 to be able to heat the building just by the air ventilation system. However, this solution would present an extreme solution in the Arctic as it would require using some unrealistic technical solutions. Nevertheless, whichever ambitious goal is chosen, the first step when designing a building in the Arctic should be to minimize the heat loss by applying highly efficient insulation. Along with insulation there must also be good air tightness of the building envelope, although this has hitherto not had enough focus in Arctic constructions. Other key elements are the utilisation of passive solar and internal gains, and the installation of a mechanical ventilation system with heat recovery. The heat recovery system is still not a normal part of the usual design strategy in the Arctic. When mechanical ventilation systems with heat recovery are used, it is critical that the installations are properly carried out, and that frost problems are avoided, such that the system efficiency become as anticipated. The last key element of the building design is solar radiation which may offer a free heat gain that may be significant compared to the potentially large transmission heat loss through the windows. These key elements are well-known from buildings in other climates, but they are not less important for energy efficient buildings located in the extreme climates.

7. Acknowledgments

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