Development and Testing of Sustainable Envelope and Climatic Systems for New Arctic Building Practice

Final report to the Bjarne Saxhofs Fond

Martin Kotol

Energy and Services
DTU Civil Engineering
Building 118
Brovej, 2800 Kgs.Lyngby
mrko@byg.dtu.dk

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Preface

The project "Development and Testing of Sustainable Envelope and Climatic Systems for New Arctic Building Practice" was carried out at DTU Byg in the period form 1.9.2016 until 31.12.2018.

The aim of the project was to study envelope systems for the Arctic buildings which can sustain the harsh conditions along with the renewable energy concepts for heating and ventilation in the Arctic dwellings. The work was conducted through a series of case studies and experiments that resulted in several reports and a scientific publication.

This report summarizes the main findings. It is supplemented with the reports and journal publication that emerged from the research work.

The project was financed by Bjarne Saxhof Foundation.

1. Introduction and objectives

There are many challenges in the Arctic regions when designing and constructing buildings and Greenland makes no exception. The temperatures frequently drop tens of degrees below zero for several months which in combination with winds often over 25 m/s results in high demand on air tightness, thermal insulation and statical strength of building envelopes. Some regions get little to no daylight during the winter, and the sun never sets in the summer which makes it difficult to use solar energy systems and leads to frequent summer overheating. In addition to the climatic challenges, logistical challenges must be faced. All transportation to/from and within Greenland is carried out at sea or air routes. Since most building materials are imported, it is obvious that the logistical challenges and costs play a significant role in the economical sustainability of construction.

With the increasing prices of energy and upcoming update of the Greenlandic building regulations the building envelopes will have to change radically to become more airtight and thermally resistant. Equally important is that the new envelopes must be to a certain degree vapor tight. Vapor that penetrates the construction might result in high relative humidity or even condensation and moisture accumulation within the building materials. This can have two consequences, one of which is the reduction of the thermal resistance and increased heat loss. The second problem is an increased risk of mold growth which affects human health and leads to the deterioration of building material by increasing porosity and reducing strength and durability.

Addressing these issues will require new or adapted envelope constructions. The future constructions should also be economically sustainable. The cost for material, labor and shipment of the future constructions will be higher than the cost for the common-practice constructions under the current building regulations. It is therefore a question whether the energy savings will be able to compensate for the extra costs and offer a reasonable return on the investment.

The increased airtightness of the new construction combined with the occupants of Arctic buildings being hesitant to ventilate by windows calls for balanced mechanical ventilation systems. These should be robust enough to sustain the extreme conditions while providing satisfactory energy performance and indoor climate. The experience from the existing buildings shows us that many systems used in Greenlandic dwellings were simply imported from southern markets and have large problems with freezing of the heat exchangers or/and low heat recovery efficiency that results in higher heat losses. Investigation of best practice solutions and proper Arctic design is therefore needed.

It is also a common problem that advanced solutions are purchased and installed with the intention to preserve energy, but their operation and maintenance is neglected leading to breakdowns. Or it is not sufficiently communicated to the users how to use these solutions. This then results in a user frustration and disbelief in the technology and can lead to disregard of the solution and higher energy consumption instead of savings. A typical example are thermostatic radiator valves. It is surprisingly common to see an open window over a radiator with thermostatic valve. In the Arctic this causes a stream of very cold outside air to wash the valve resulting in full opening of the valve and hot air from fully powered radiator just escaping the room through the opened window.

To contribute to solving some of the present challenges the following objectives were formulated for this project:

1. To develop and evaluate a new envelope system for the Arctic buildings which can sustain the harsh conditions yet capable of reducing the heat demand to a minimum
2. To select test the most promising renewable energy concepts for buildings in the Arctic
3. To develop and evaluate energy efficient heating and ventilation systems for the Arctic dwellings

Originally, the project was designed to be adjacent to a large Arctic Building and Construction project[1] where a new test house in Nuuk, GL was to be constructed and new technologies tested. Unfortunately, due to delays in the overarching project it was necessary to untie the two projects in order to be able to continue. Nevertheless, we focused on the original objectives as much as possible given the challenge of missing the test house.

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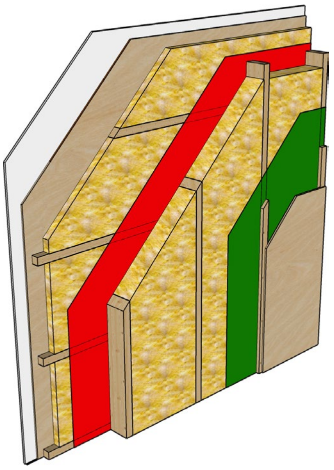
[1] https://arctic.dtu.dk/english/research/research-projects/arctic-building-and-construction-practice

2. Methods

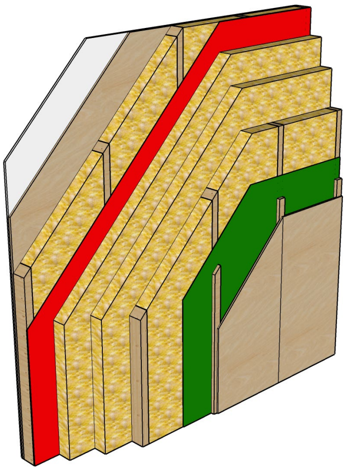
2.1. Sustainable Wall Constructions in Arctic Climates

The first objective was addressed in a study of **Sustainable Wall Constructions in Arctic Climates** where 5 new wall designs were analyzed and evaluated against a traditional wall construction used nowadays. Hygrothermal as well as economic analysis were performed on the following wall types:



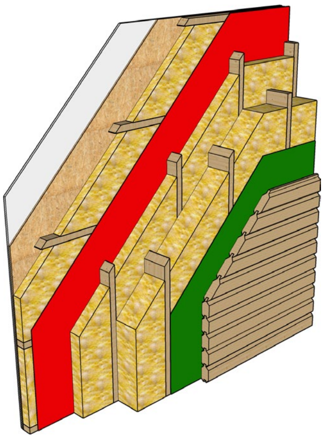
	Material	Properties				
		$d[mm]$	$\lambda[\frac{W}{m*K}]$	$\mu[-]$	$\rho[\frac{kg}{m^3}]$	$c_p[\frac{J}{m^3*K}]$
1	Gypsum board	12	0,21	10	700	1000
2	Plywood board	12	0,13	200	500	1600
3	Insulation with horizontal battens [50/50] c/c 610mm	50	0,037 0,13	1 50	16 500	1030 1600
4	Vapour barrier	0,2	-	700.000	-	-
5	Insulation with vertical studs [50/150] c/c 610mm	150	0,037 0,13	1 50	16 500	1030 1600
6	Air barrier	0,5	-	0,35	-	-
7	Ventilation gap	25	-	-	-	-
8	Façade cladding	12	-	-	-	-

Figure 1 – GBR 2006 wall. This wall represents a common Greenlandic building practice and was designed to fulfil the requirements of the current Greenlandic building regulations of 2006.



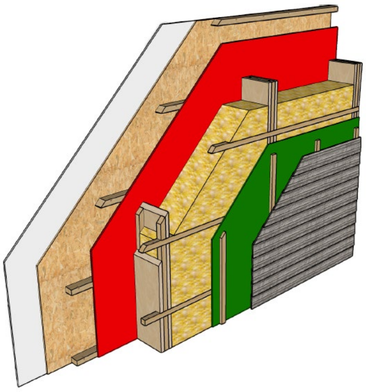
	Material	Properties				
		$d[mm]$	$\lambda[\frac{W}{m*K}]$	$\mu[-]$	$\rho[\frac{kg}{m^3}]$	$c_p[\frac{J}{m^3*K}]$
1	Gypsum board	12	0,21	10	700	1000
2	Plywood board	15	0,13	200	500	1600
3	Insulation with vertical studs [50/100]	100	0,037 0,13	1 50	16 500	1030 1600
4	Vapour barrier	0,2	-	700.000	-	-
5	Insulation	200	0,037	1	16	1030
6	Insulation with vertical studs [50/100]	100	0,037 0,13	1 50	16 500	1030 1600
7	Air barrier	0,5	-	0,35	-	-
8	Ventilation gap	25	-	-	-	-
9	Façade cladding	12	-	-	-	-

Figure 2 - GBR 2020 wall. This is an advancement of the GBR 2006 wall that meets the upcoming criteria. The two main improvements are a thicker insulation layer and a reduction of the thermal-bridge effect of the wooden studs by using two layers of wooden studs with layers of undisturbed insulation between them.



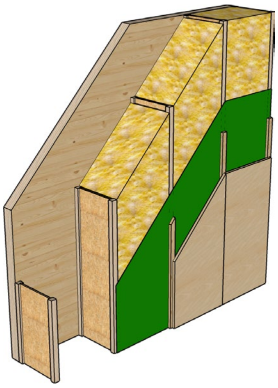
	Material	Properties				
		$d[mm]$	$\lambda[\frac{W}{m*K}]$	$\mu[-]$	$\rho[\frac{kg}{m^3}]$	$c_p[\frac{J}{m^3*K}]$
1	Gypsum board	12	0,21	10	700	1000
2	Plywood board	12	0,13	200	500	1600
3	Insulation with vertical studs [50/100]	100	0,037 0,13	1 50	16 500	1030 1600
4	Vapour barrier	0,2	-	700.000	-	-
5	Insulation	200	0,037	1	16	1030
6	Insulation with vertical studs [50/100]	100	0,037 0,13	1 50	16 500	1030 1600
7	Air barrier	0,5	-	0,35	-	-
8	Tongue-and-groove cladding	71	0,13	50	500	1600

Figure 3 – Scanwo wall. The difference between the Scanwo wall and the two GBR walls is that the Scanwo wall has no ventilated façade. In this case, the external rain screen is created by a layer of stacked tongue-and-groove timber.



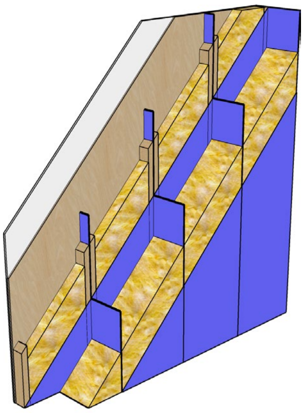
	Material	Properties				
		$d[mm]$	$\lambda[\frac{W}{m*K}]$	$\mu[-]$	$\rho[\frac{kg}{m^3}]$	$c_p[\frac{J}{m^3*K}]$
1	Gypsum board	12	0,21	10	700	1000
2	OSB board	12	0,13	200	650	1700
3	Installation (air) with horizontal batten [45/75]	75	0,389 (0,025) 0,13	1 50	1,23 500	1008 1600
4	Vapour barrier	0,2	-	700.000	-	-
6	Insulation with vertical LVL [111/300]	300	0,037 0,13	1 50	16 500	1030 1600
7	Air barrier	0,2	-	0,35	-	-
8	Ventilation gap	25	-	-	-	-
9	Facade cladding	12	-	-	-	-

Figure 4 – Masanti wall. A timber frame, assembled from core-insulated columns (made of LVL). On the inside, adjacent to the vapor barrier, is a hollow space for installations. On the outside, the assembly is finished by an air barrier and a ventilated façade.



	Material	Properties				
		$d[mm]$	$\lambda[\frac{W}{m*K}]$	$\mu[-]$	$\rho[\frac{kg}{m^3}]$	$c_p[\frac{J}{m^3*K}]$
1	CLT [16]	100	0,13	40-80[1]	500	1600
2	Insulation with vertical I-joist [50/360]	360	0,037 0.13	1 50	16 500	1030 1600
3	Air barrier	0,5	-	0,35	-	-
4	Ventilation gap	25	-	-	-	-
5	Facade cladding	12	-	-	-	-

Figure 5 – CLT wall. The specific characteristic of this wall is that no vapor barrier is mounted on the inside. Due to its thickness, the wooden-disc elements act as vapor breaks.



	Material	$d[mm]$	$\lambda[\frac{W}{m*K}]$	$\mu[-]$	$\rho[\frac{kg}{m^3}]$	$c_p[\frac{J}{m^3*K}]$
1	Gypsum board	13	0,21	10	700	1000
2	Plywood board	12	0,13	200	500	1600
3	Insulation with horizontal battens [45/90]	90	0.037 0.13	1 50	16 500	1030 1600
4	Fiberglas casing	3	0,19	10000	1400	1200
5	Insulation	300	0.037	1	16	1030
6	Fiberglas casing	3	0,19	10000	1400	1200

Figure 6 – FIBRA wall. This system uses prefabricated fibre-glass laminate boxes with a high density rock-wool insulation as a core and a gel coating on the outside-facing surface. The boxes are load bearing and mounted on site by gluing them together.

U-values of each wall were calculated by hand calculations according to DS 418:2011 and using finite element method-based software HEAT3. The vapor transfer through the constructions was then analyzed following the standard DS/EN ISO 13788. According to this standard the moisture transfer trough the wall sections is considered steady state. The basic approach is to compare the saturation water-vapor pressure $p_{v;sat}$ and the actually occurring water-vapor pressure $p_{v;x}$ at different interfaces in the wall sections. The calculations were performed for each month of a year and for a standard value using the following input data:

	Standard	January	February	March	April	May	June	July	August	September	October	November	December
$T_{out}[°C]$	-30	-14,7	-17,8	-15,3	-6,6	-0,8	3,7	6,2	5,7	3,1	-1,7	-5,8	-9,5
$\varphi_{out}[\%]$	80	70,0	69,5	61,8	69,2	60,7	82,8	76,3	85,8	79,4	77,4	74,9	66,0
$T_{in}[°C]$	20	20	20	20	20	20	20	20	20	20	20	20	20
$\varphi_{in}[\%]$	50	50	50	50	50	50	50	50	50	50	50	50	50

For economical sustainability assessment it was assumed that a new wall construction with a lower transmission heat loss than the current building practice, can be seen as economically sustainable when the lower heat loss is sufficient to regain the additional investment that had to be made for the new wall within its lifetime. The lifetime of an exterior wall of a domestic building was for this purpose assumed to be 50 years. To assess the economical properties of the different construction methods it was decided to investigate different U-value alterations of the same construction principle. These alterations have been designed for each construction principle for the values of approximately 0.080, 0.100, 0.130, 0.170 and 0.200 [W/(m^2.K)] (the exact U-values were calculated using closest realistic insulation thicknesses). Furthermore, the vapor transfer of the alterations has been checked by means of the vapor-transfer hand calculations as described above to assess the risk of potential moisture problems. Since material prices and labor costs depend on the scale of the project, an identical wall assembly will most likely have different square-metre prices depending on the size of the building or the number of buildings in one project. Therefore, case building has been chosen as a basis for the cost estimations. The chosen building is the Illorput 2100 V2 (Figure 7). This type house was developed and can be purchased in Greenland, and it is subsidised by the Greenlandic government.

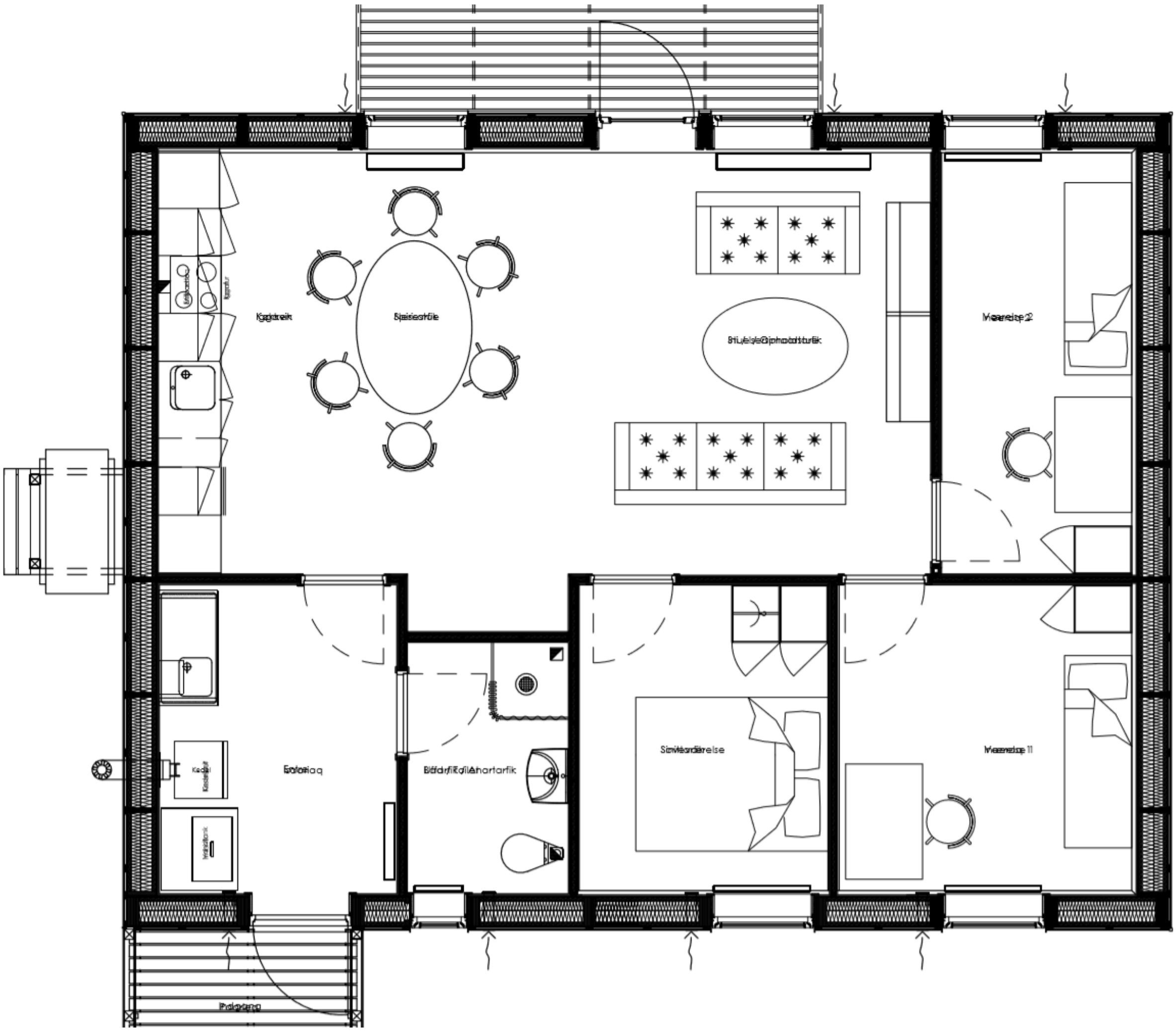


Figure 7 - Illorput 2100 V2 type house (state: 28.02.2016); source: Consulting – Sanaartornermik Siunnersuisartut, Postboks 3561, 3911 Sisimiut, mail: info@2s.gl, Tlf.: +299 86 35 60

In order to assess the economical sustainability of the walls and their alterations, the amortisation period for each wall was calculated in comparison to a reference wall. Although the initial investment costs of the evaluated walls are higher than that of the reference wall, expected annual savings in heating costs make up for this price difference in the long run.
The material and labour costs for the wall types and their alterations have been obtained using prices and man hours from the software database V+S Prisdata for Greenland.
The shipping costs were calculated according to the Royal Arctic Line price lists. Goods with a weight of up to 600 [kg/m^3] are accounted for according to their volume. All goods that are heavier than this are accounted for according to their weight.

2.2. Mechanical ventilation heating as a substitute for traditional waterborne heating solutions in Greenland

The second and third objectives were addressed by multiple case studies in Sisimiut and Nuuk.
In the study of **Mechanical ventilation heating as a substitute for traditional waterborne heating solutions in Greenland** we studied the possibility of using mechanical ventilation heating as a substitute for the conventional waterborne radiator systems used in Greenland. For this study a modern building built in Sisimiut was selected (Figure 8) and modelled using a dynamic simulation software, IDA ICE.

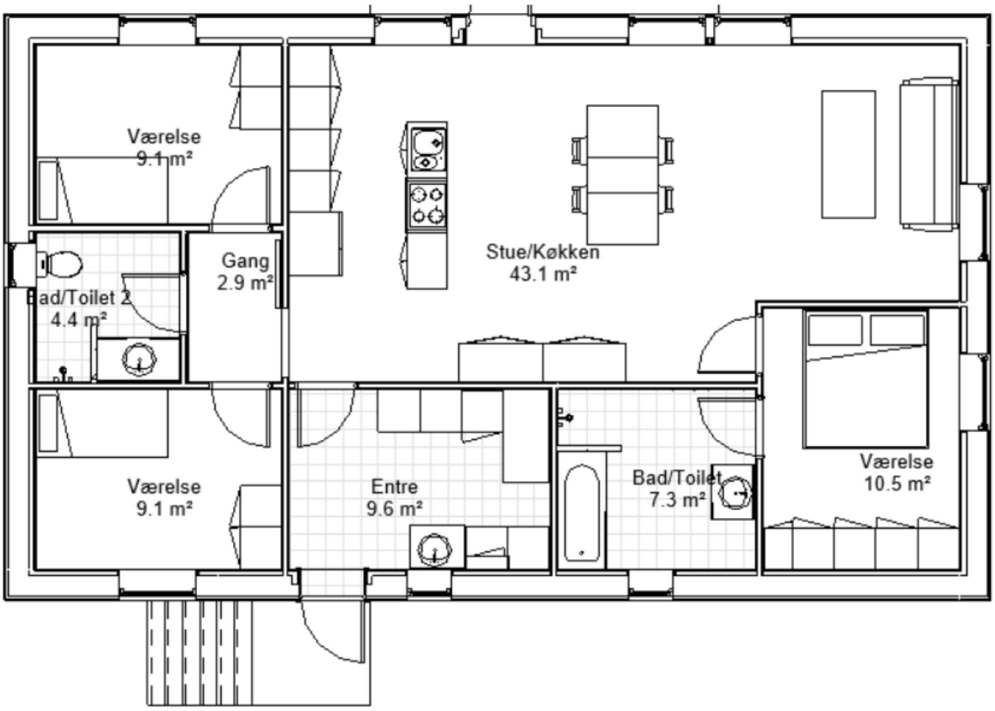


Figure 8 – Case building in Sisimiut

To determine whether the building can be heated by ventilation a conceptual model was designed (Figure 9). The ventilation rates were calculated based on the room design heat losses at -30 °C and supply air temperature of 50 °C. Three scenarios were modelled and studied:

Table 1 – Modelled scenarios

Version #	Envelope type	Heating system	Ventilation system
Reference	Default	Default heating system, radiators	Mechanical constant ventilation with heat recovery
Central heat coil	Default	Electric heating ventilation, one centralised Heat coil	Mechanical balanced ventilation with heat recovery
Zone heat coils	Default	Zone specific electric heat coils in ventilation system	Mechanical balanced ventilation with heat recovery

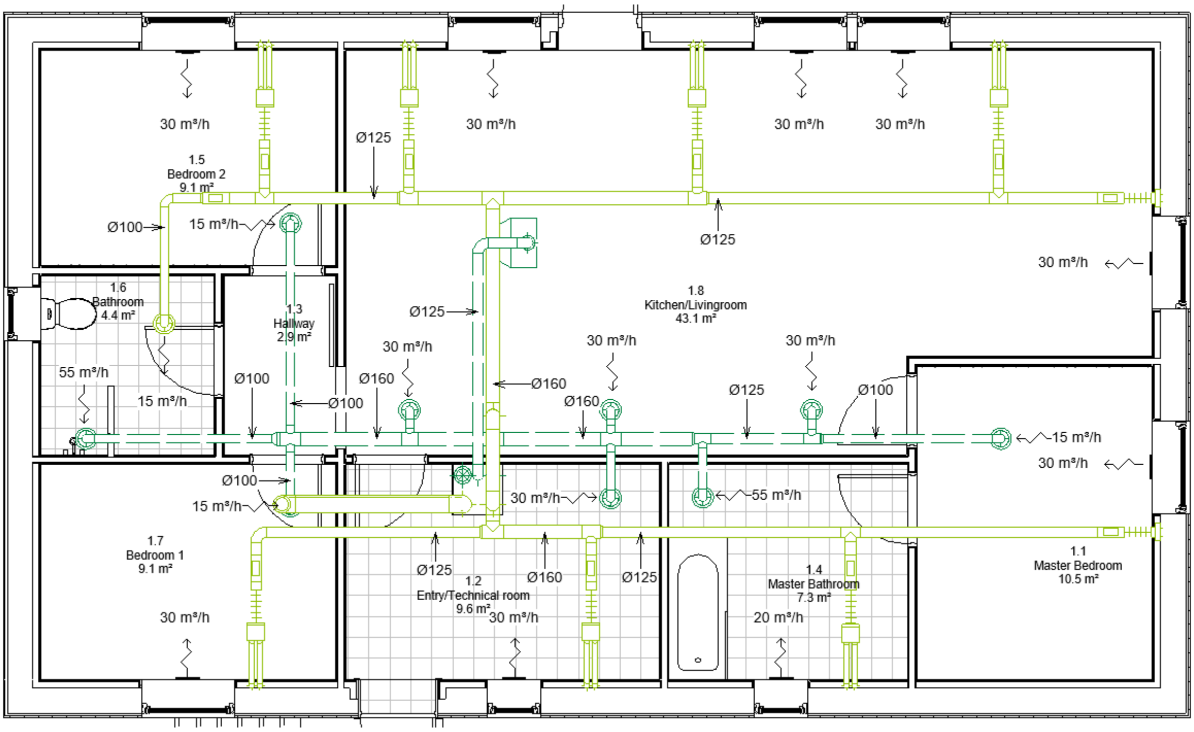


Figure 9 - Ventilation system layout

Due to the deterministic nature of simulation in IDA ICE, the output of the simulation will always be equal to the input specifications. It is thereby difficult to determine the energy consumption of the system in terms of user interactions with building properties in particular window opening behavior. It was therefore decided to implement a stochastic variable model. The window control macro was applied to all bedroom windows in all three models. Since window opening is not a completely defined term; it was defined as 10% opening of the total window area in the horizontal direction for the simulation. Furthermore, an economic analysis was made to compare the costs of the 3 versions. To assess the economics for the building systems, the program Sigma Estimates were used along with Molio Prisdata, which is a database of mean prices for different jobs and materials, that can be used to make estimates of the building costs. Because the ventilation heating systems are rather unconventional in Greenland, some estimates had to be done, such as the time spent on installation of the system and costs of assembly of the systems.

2.3. Niviarsiat elderly home

In the **Niviarsiat elderly home** study we studied the heating consumption in a complex of 4 apartment buildings for elderly people (Figure 10). This complex was chosen for its recent introduction of individual heating bills. Consequently, the tenants that live in identical apartments started receiving heating bills that differed by up to 350%. We performed a questionnaire survey along with interviews with the occupants in order to identify reasons for such significant energy use differences. Energy use data were provided by the public housing company INI A/S. This study was followed by a public seminar where we presented the results to the occupants and held a lecture on energy preserving behaviour for the elderly people.

Figure 10 – Niviarsiat elderly complex

2.4. Evaluation of room based mechanical ventilation with heat recovery

In the **Evaluation of room based mechanical ventilation with heat recovery** we studied the suitability of the decentralized small ventilation units in the Arctic conditions through a case study in Nuuk. These units are often marketed as a solution for indoor air quality improvement in Greenland. They comprise of a single bi-directional ventilator and a ceramic element that acts as a heat accumulator hence certain degree of heat recovery is promised. The air flow switches between supply and return in 70 s intervals.

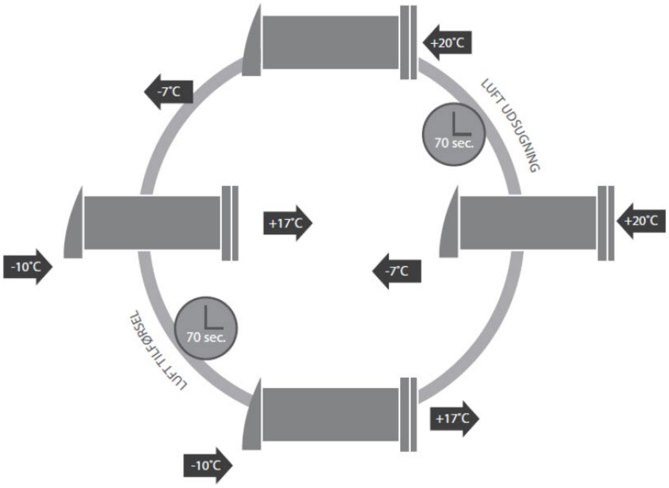


Figure 11 - Work principle of the decentralized ventilation unit

For the evaluation we selected two neighbouring apartments with identical structure, as well as an approximately the same resident composition. The apartments are from 1998 and were built according to the standard of the time with mechanical exhaust through bathroom and range hood and inlet through fresh air valves on the facade. The envelope is a light wooden construction with a total of 195 mm of thermal insulation. The apartments are on two levels and comprise of an entrance hall/utility room, kitchen and living room on the ground floor. The first floor consists of a bathroom and 3 bedrooms. The gross floor area is 81 m^2. The living room has a net area of 19 m^2, while the kitchen is 10 m^2. The location of the two fresh air vents that were replaced by ventilation units is shown in Figure 10. Both homes are heated with direct electric heaters.

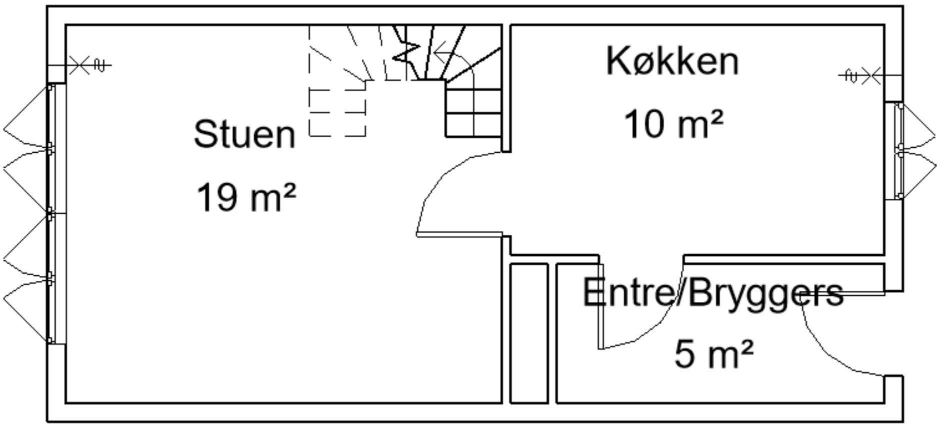


Figure 12 - Ground floor plan

Measurements of Temperature, RH and CO$_2$ in both apartments were made in two periods. Initially, it was measured in 20 days, to form a baseline for comparison. Then existing fresh air valves were replaced with decentralized ventilation units in kitchen and living room of one of the apartments and additional 40 days of measurements were conducted. To evaluate the thermal efficiency of the heat recovery unit inside the ventilation, sensors were placed inside the unit as well. The occupants were interviewed during the experiment to receive feedback on user experience.

2.5. Current ventilation strategies in Greenlandic dwellings

Finally, the study **Current ventilation strategies in Greenlandic dwellings** brings an overview of commonly used ventilation tactics in Greenland. We studied ventilation systems in three different homes. Two of the homes are existing row houses renovated for better IAQ. The third building is a newly built single-family home. The ventilation systems represent the state-of-the-art solutions currently used in small to medium Greenlandic dwellings (buildings with less than 4 apartments). All experiments took place during winter period (between December and February). The IAQ in the rooms was monitored with an indoor environment monitoring sets comprising of a) CO$_2$ sensor b) Temperature/RH/2 External channels data logger. The logging interval was set to 5 minutes. Interviews with the occupants were conducted in an informal manner since the number of occupants was small and the cases differed. They took place when we collected the monitoring equipment at the end of the experiments.
The first building in the study is a row house in Tuapannguanut – Sisimiut built in 80’s. It consists of two floors. In a ground floor, there is an entrance, laundry, living room and kitchen. On the second floor there are two bedrooms and a bathroom (see the floor plans in Figure 12). The floor area of the

home is approximately 70 m². The house is occupied by a family of seven people (2 adults and 5 children). The original ventilation system consisted of fresh air valves (FA) in bedrooms and living room, range hood and two vertical ventilation shafts from bathroom and laundry room (EA).

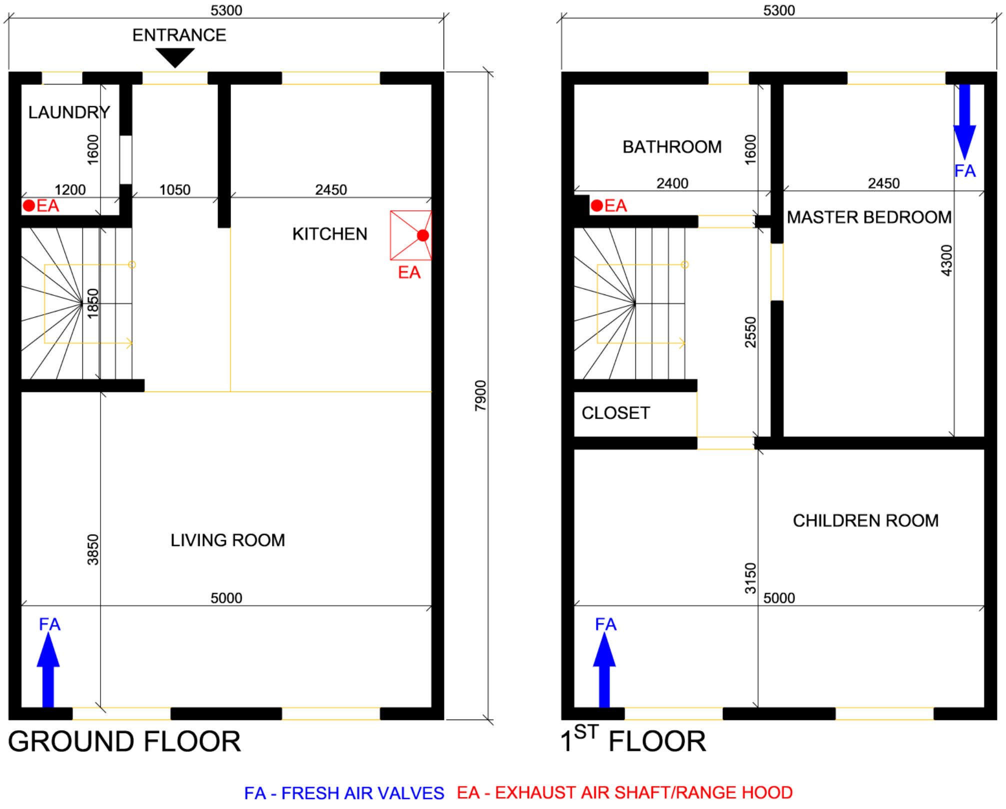


Figure 13 - Case building 1 - Floor plans

The ventilation system was replaced with balanced ventilation system using a ventilation unit with a rotary heat exchanger. Fresh air is supplied into the two bedrooms and to the living room. Exhaust terminals are placed in the kitchen, bathroom and laundry. The range hood remained connected directly to outside and was not part of the installation. The existing fresh air valves on the façade were sealed. The ventilation unit is equipped by a controller, which allows the users to choose from 3 operation modes (see Table 2). The occupants do not have the option of turning the ventilation system completely off. In addition to the controller there is a hygrostat placed in the bathroom, which activates the “Boost” mode at RH above 60%.

Table 2. Ventilation unit modes

Mode	Speed [%]	Air flow [m³/h]	Air change [h^{-1}]
Away	25	36	0.19
Home	55	120	0.63
Boost	80	180	0.95

The measurements of IAQ (T;RH and CO_2) and interviews with the occupants took place before and after installation of the ventilation unit during winter period. The ventilation unit was set to mode “Home” during the entire measurement period.

The second building in our study is a newly built (2018) single family home. It is a 120 m^2 single story building that consists of three bedrooms, two bathrooms, an entrance and a kitchen/dining/living room. The building is ventilated by balanced mechanical ventilation system with ventilation unit with rotary heat exchanger (the unit is identical to the one used in Building 1). Similarly to Building 1, also here the ventilation channels are made of semi-flexible plastic ducts of small diameter (d_{in}= 63 mm). Ventilation schematics can be seen in Figure 13.

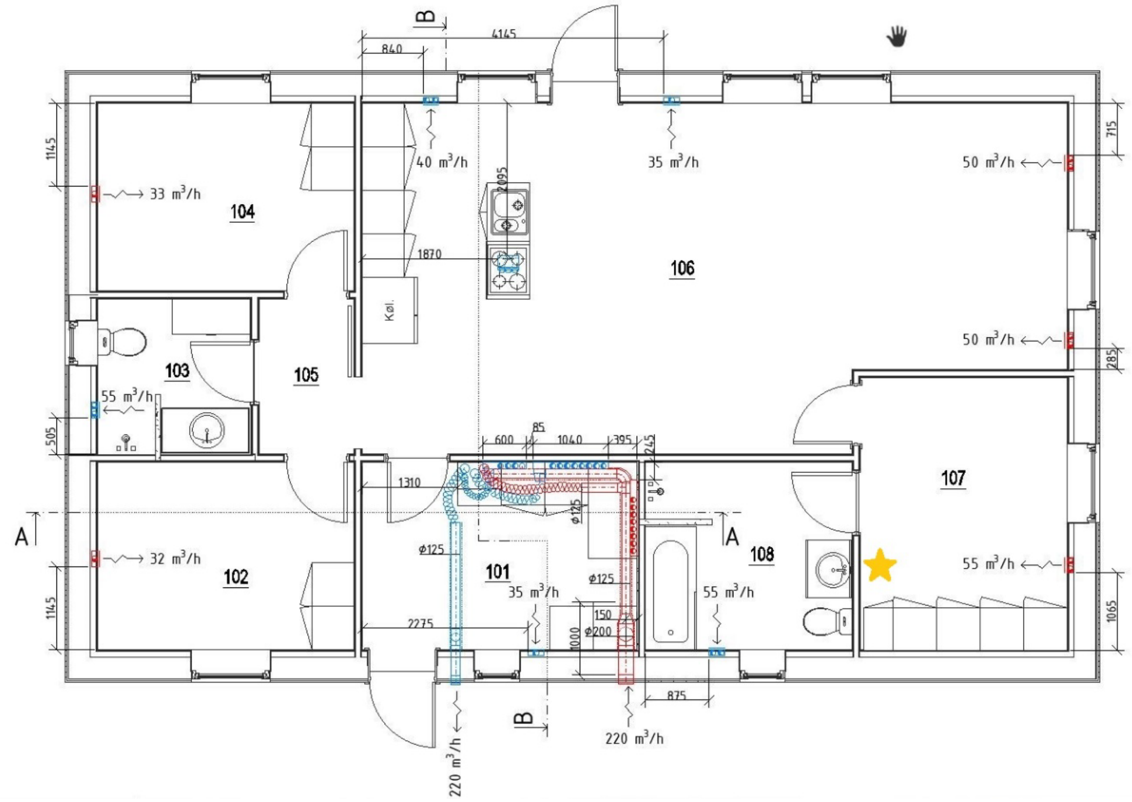


Figure 14. Building 2 - Ventilation schematics - Floor plan. The star indicates placement of the IAQ meter.

In this building, the range hood is connected to a designated fifth port in the central ventilation unit. The occupants were interviewed about their user experience with the ventilation system and perceived IAQ. Additionally, temperature, RH and CO_2 concentration was monitored in the master bedroom for a period of 1 week during winter period. The ventilation unit was set to mode "Home" during the entire measurement period.

The third building is a two-story row house built in 80's. The total floor area is 60 m^2. In the ground floor, there is an entrance, bathroom, kitchen and living room. First floor then comprises of two bedrooms and two storage rooms (see Figure 14). The building is occupied by a family of 2 adults and 2 children. The original ventilation principle was identical to the one in Building 1. Fresh air valves (FA) in combination with mechanical range hood and natural exhaust from bathroom via ventilation shaft (EA).

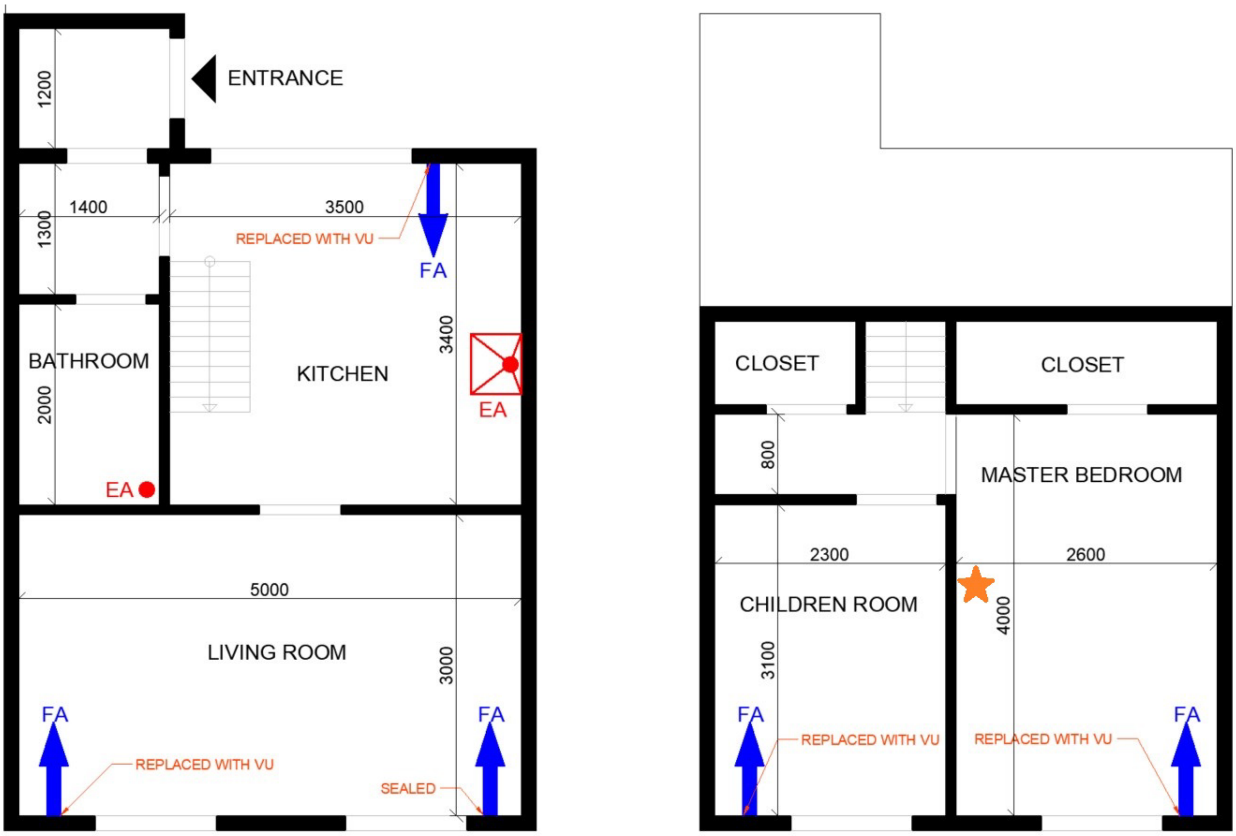


Figure 15. Building 3 - Floor plans. The star indicates placement of the IAQ meter.

In this case, the renovation consisted of installation of 4 decentralized (one-room) ventilation units (VU) in the façade (Figure 8). The existing fresh air inlets were used to accommodate the new ventilation aggregates as shown in Figure 14. The existing range hood and natural ventilation shaft in the bathroom remained unchanged.

Figure 16. Schematics of the decentralized ventilation unit

The ventilation units run in two cycles. Cycle 1 – the built-in ventilator blows the fresh air into the building. Cycle 2 – The direction of the fan changes and air is being extracted out of the building. The cycles switch at the interval of 70 s. Inside the device, there is a ceramic based element that acts as a heat and moisture recovery. It accumulates heat and moisture of the extract air (during cycle 2) and reintroduces it to the fresh air (during cycle 1). To maintain pressure balance inside the house the 4 units are synchronized in a way that when two of them run in cycle 1, the other two run in cycle 2. The speed of the ventilators can be adjusted in three steps as shown in Table 3. The provided air change was calculated assuming two of the ventilation units in cycle 1 and two units in cycle 2.

Table 3. Ventilation speeds

Speed	Air flow of one unit [m^3/h]	Air change [h^{-1}]
1	10	0.14
2	20	0.28
3	30	0.42

The IAQ in master bedroom was monitored before and after the installation. The temperature of the air supplied via the unit was measured in 2-second intervals to evaluate the efficiency of the heat recovery and identify risks of cold draught. Additionally, the occupants were interviewed to get an overview of the user satisfaction with this solution. During the measurement period all units were set to the maximum speed.

3. Project dissemination

At first a seminar for elderly people was held in Sisimiut with the intention to educate them in user behavior and it’s effects on heat consumption. In this seminar Greenlandic students from DTU explained to the elders for example how modern thermostatic valves work and how to set them up to reduce heating costs without sacrificing comfort. Secondly, a seminar for professionals was held in conjunction with E-Lighthouse[2] project meeting in Sisimiut where results of our research were presented to local and international stakeholders. Thirdly, several reports, thesis and a journal article were published. For details see Table 1. Finally, the obtained knowledge is being shared in building courses within Arctic Engineering education at DTU in Greenland.

Table 4 - List of publications (attached at the end of this report)

Nr.	Title	Type	Date	Objective addressed
1	Sustainable Wall Constructions in Arctic Climates	M.Sc. thesis	7.2018	1
2	Mechanical ventilation heating as a substitute for traditional waterborne heating solutions in Greenland	B.Eng. Thesis	6.2019	2+3
3	Niviarsiat elderly home	Report	12.2017	3
4	Evaluation of room based mechanical ventilation with heat recovery	B.Eng. Thesis	6.2020	3
5	Current ventilation strategies in Greenlandic dwellings	Journal	7.2021	3

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[2] http://www.elighthouse.eu/

4. Main project results and discussion

4.1. Sustainable Wall Constructions in Arctic Climates

The analysis of the U-values showed that the GBR 2020, CLT and the Fibra walls will meet the upcoming requirements of the new Greenlandic building regulations. These walls will also not require the roof and/or floor constructions to compensate in order to meet the required overall transmission heat loss of the building. The Scanwo and Masanti wall construction would require the roof and/or floor constructions to compensate for its higher U-value in order to meet the overall requirements for the transmission heat loss.

The results of the vapor transfer analysis showed that, in terms of usability, the Masanti, CLT and Scanwo walls can be considered suitable for the local climatic conditions. The GBR 2020 wall was found to be usable but to bear the risk of mold growth during some months of the year. However, this issue could be fixed by small adjustments in the construction design. For the Fibra wall construction it was found that the results for the vapor transfer analysis depend highly on the material properties of the resin-coated glass-fiber construction. For the used material properties, it was found that the polyester resin makes the construction unusable under the local climatic conditions. However, the same calculation with a phenolic resin on the inside and a polyester resin on the outside improved the vapor transfer. For the Fibra wall, it can therefore be concluded that thorough laboratory tests would be beneficial to establish the actual material properties and the vapor transfer through the fiberglass reinforced resin boxes.

Additionally, it was found that the rule of thumb to place the vapor barrier within the first third of the wall construction does not necessarily apply to every construction type. The results from GBR 2006, GBR 2020 and the Fibra wall show that the vapor barrier should be located closer to the inside in order to avoid too high relative humidity near the vapor barrier.

The economic analysis showed that decreasing U-value leads to increase of shipping cost for all wall types due to larger volumes of insulation. The shipment costs lay between 20% and 25%. The share of the labour cost has decreases with increasing U-values. For the CLT wall, the share of the material costs is the highest and lays between 45% and 50%. Whilst the GBR 2020 walls have the lowest share of material cost and never exceeds the 40% mark.

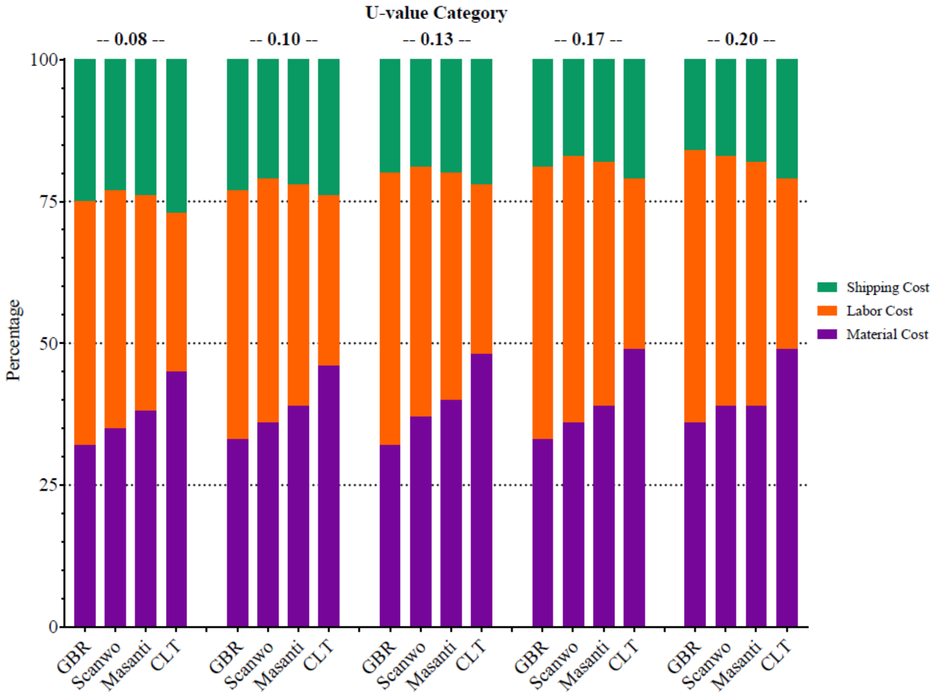

Figure 17 - Composition of the wall construction types total cost

The years until amortization of each wall type when plotted against the U-value category create a curve. The fact that these curves are uneven is explained by the circumstance that the total cost of a wall type does not increase in the same manner between the different U-value categories. It is evident that for each construction type, an optimum U-Value exist with the fastest amortization time in comparison to the initial investment.

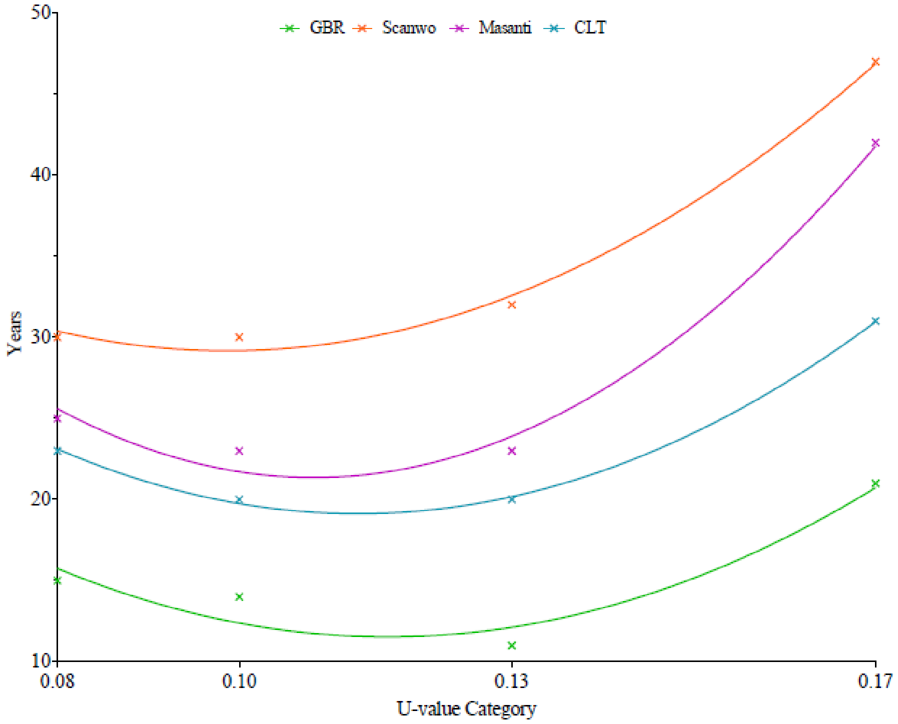

Figure 18 - Amortisation time of the construction methods for the scenario with a steady

To conclude it was found that the Scanwo and CLT walls are suitable for the climatic conditions and fulfil the requirements of the upcoming building regulations. The Scanwo wall shows a slightly increased risk for condensation in the wooden cladding under the “worst case scenario” conditions due to the lack of ventilated cavity. The Masanti wall was also found suitable but, does not meet the requirements for U-value. The Fibra wall was first found to experience critical internal condensation. However, uncertainties regarding the actual used building and applicability of the calculation method led to the conclusion that no statement about the Fibra wall can be given without further testing. The GBR 2020 wall was found to bear the risk of mold growth. However, it can be considered suitable because a small adjustment in the structure could eliminate this risk. The economic analysis showed that the five walls and almost all their U-Value alterations can be amortized within the assumed building-lifetime of 50 years. Another important conclusion can be drawn. This is that it is not possible to give a clear answer to whether or not a wall-construction type is suitable for the Arctic in general. The differences in climatic conditions, quality of the infrastructural connection to the rest of the world and the ability of the homeowners to carry out the construction work themselves are the determining factors for whether or not the construction principle is suitable. Especially architects and engineers therefore have to discard the notion of the Arctic as one single region with homogeneous demands to the designs.

4.2. Mechanical ventilation heating as a substitute for traditional waterborne heating solutions in Greenland

Table 5 - Annual energy data

Model	Consumption [kWh]	Consumption [kWh/m²]	Highest month [kWh]	Lowest month [kWh]	Heat Recovered [kWh]
Reference	21142	220.3	2652	388	9893
Zone heat coils	19387	202	2871	117	20111
Central heat coil	17596	183	2588	403	19549

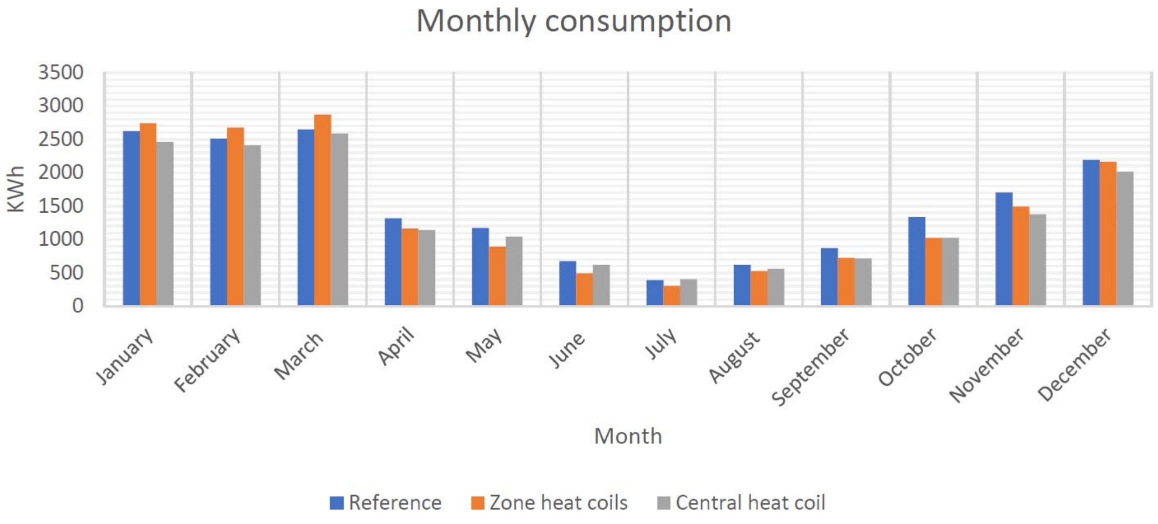

Figure 19 - Monthly heating consumption

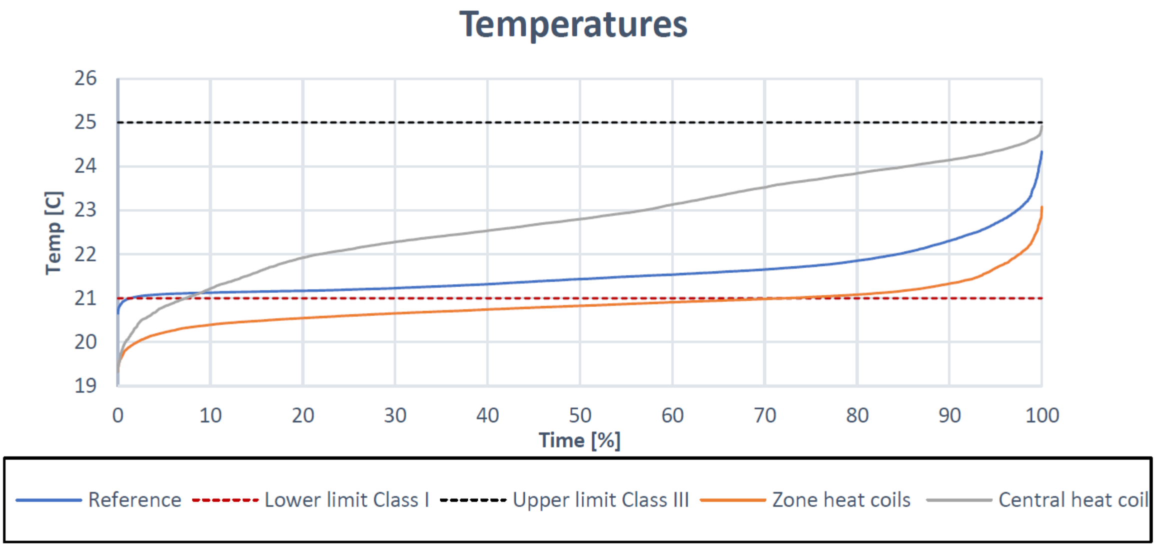

Figure 20 - Average room temperatures - cumulative curve

The results showed that ventilation heating solution with zone-specific heat coils can lower the yearly consumption of a building and improve the IAQ. However, it must be noted that the energy reduction benefits are highly dependent on the efficiency of the heat recovery unit due to increased ventilation air flows (Figure 21).

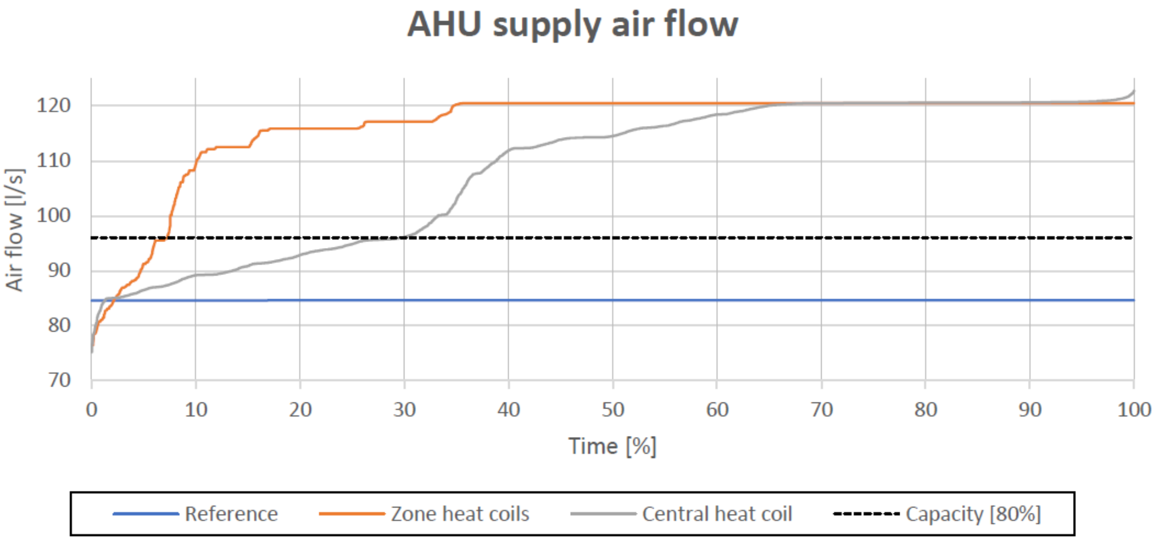

Figure 21 - Ventilation air flows

Installing a ventilation heating system would reduce the initial investment of the building and is competitive to the traditional solution over a 20-year period (Table 6). Higher running costs of the heating coil solution are caused by higher electricity prices compare to the heating oil prices.

Table 6 - Investment and running costs

Model	Initial costs [DKK]	1-year running costs [DKK/yr.]	Total cost 5 years [DKK]	Total cost 10 years [DKK]	Total cost 15 years [DKK]	Total cost 20 years [DKK]
Reference	273000	10083	323415	373830	424245	474660
Zone heat coils	217000	13151	282755	348510	414265	480020
Central heat coil	195000	12599	257995	320990	383985	446980

Careful consideration is needed in terms of location and the reasoning behind implementing such a system. The location of the building and the building envelope are undeniably important to consider, when using ventilation heating. Locations with excess of renewable energy resources and lower design temperature difference would be better suited for ventilation heating. Suggested further studies should focus on hot air heating of buildings with lower heat loss, and Greenlandic behavioural patterns and equipment usage to increase the general understanding of the behaviour of occupants in Arctic regions.

4.3. Niviarsiat elderly home

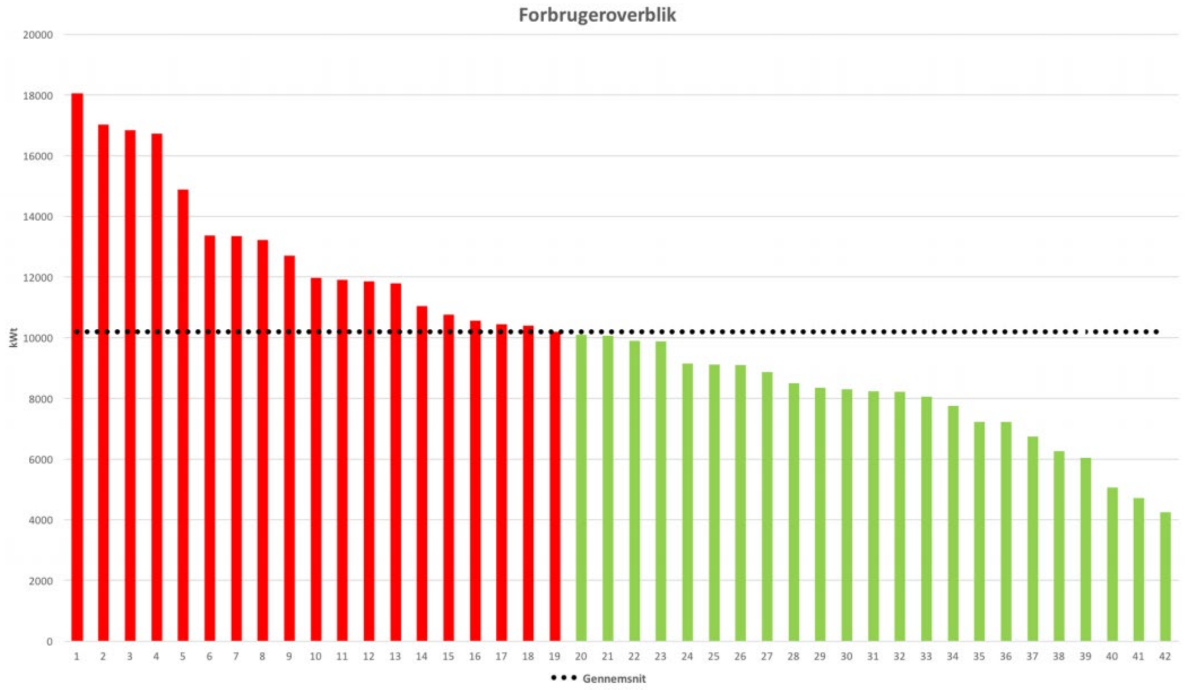

Figure 22 - Annual heating bills for individual apartments

The analysis showed that in some apartments the occupants complain about cold draught through untight building envelope which in many cases was due to open windows. Those apartments experienced higher heat loss.

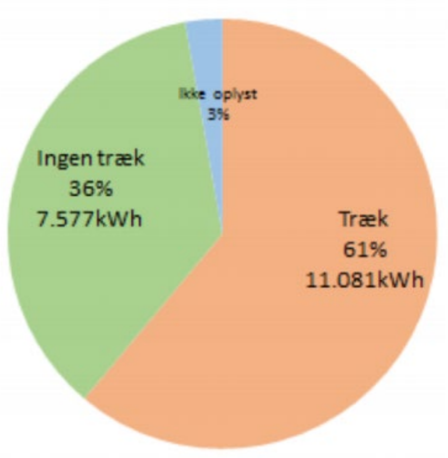

Figure 23 - Tennants complining about cold draught

Surprisingly, the majority of occupants claimed that they keep their window open at all times (which caused draught discomfort to many of them). This group also received higher heating bills than the rest.

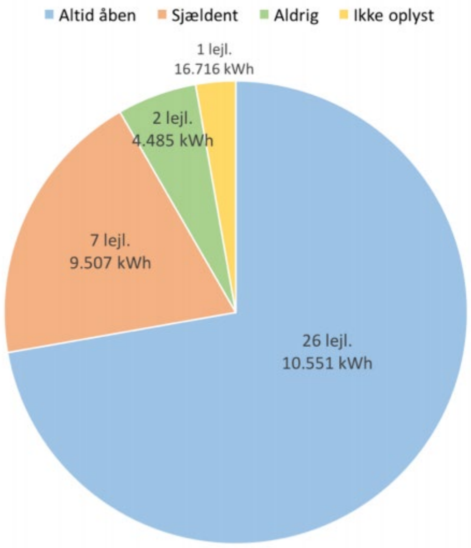

Figure 24 - Window opening habits

When interviewing the occupants we discovered that 58% of them has no knowledge about the functionality of thermostatic radiator valves. This group was also receiving the highest heating bills. In many cases we observed a winter situation (outside temperature below -20°C) where a window was kept open in the kitchen and the cold draught caused the thermostatic radiator valve to fully open. Hence the radiator was running on 100% releasing large part of the heat towards the outside through the open window. It was therefore clear that the user behaviour has a substantial effect on the heat consumption of the apartments. With the intention to reduce the heating consumption and educate the elders in functionality of their heating system we organized a workshop in which our Greenlandic speaking students explained and demonstrated some basic principles. The effects of the seminar on the actual heat consumption unfortunately remain to be evaluated within future projects.

Figure 25 - Workshop for the elders of the community

4.4. Evaluation of room based mechanical ventilation with heat recovery

The results showed that the decentralized ventilation units offer heat recovery efficiency of less than 65%. The flow direction is estimated using air temperatures on the room side of the unit. Local maxima and minima were found to identify when the fan switches from supply to exhaust. Figure 26 illustrates how the temperature drops from a maximum at 23:04:50 down to a minimum at 23:06:10, after which the temperature rises again until it reaches the next maximum again at 23:07:10. The measured temperature cycle does not alight with the expected 70 second cycle precisely. However, there are approx. 140 seconds between the local maxima, as well as approx. 140 seconds between the local minima. These points are considered indicators of two full cycles.

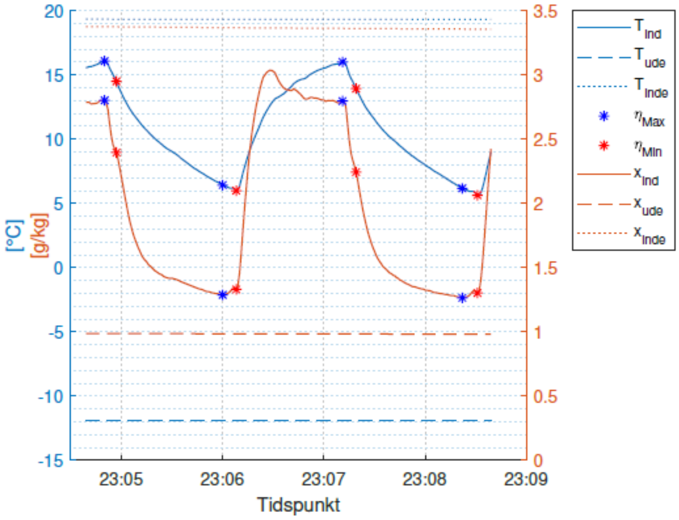

Figure 26 - Visualization of changes between supply and exhaust temperatures

Moreover, the units increased the discomfort in occupants through increased cold draught in the space and increased noise levels as confirmed by the occupants (see Figure 27).

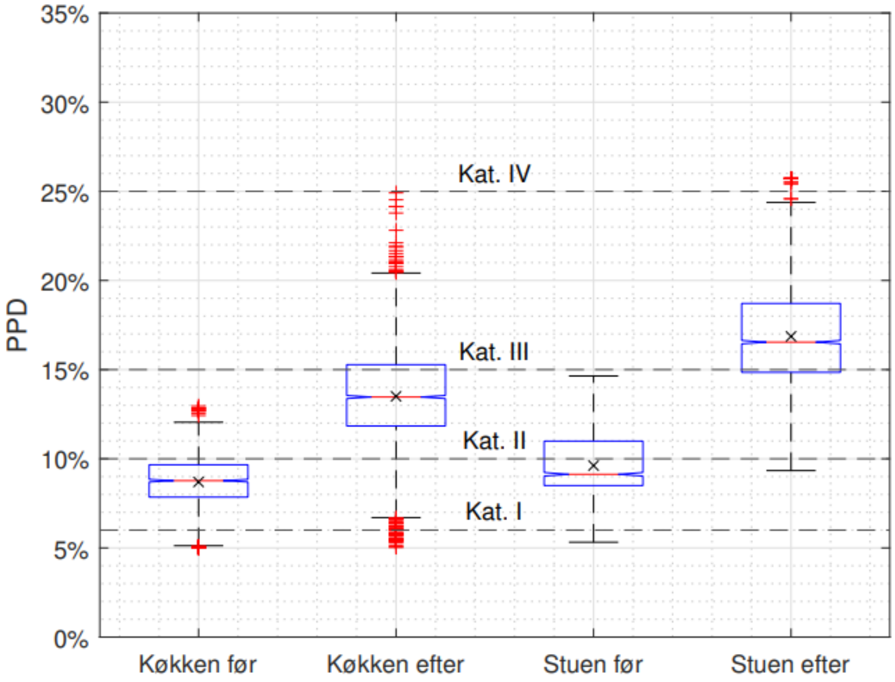

Figure 27 - Percentage of dissatisfied before and after installation of the decentralized ventilation units

The study concluded that the tested type of the wall installed decentral ventilation is not suitable for Arctic climate without significant alternations. Those should include higher heat recovery efficiency; better noise attenuation; different supply flow patterns and/or after heating of the supply air.

4.5. Current ventilation strategies in Greenlandic dwellings

In Figure 28 the CO_2 concentrations measured in the master bedrooms of the three case homes are compared with the measurements from our previous study[3]. It should be noted that each curve from our past study represents multiple dwellings whereas the new curves each represents one case. For all cases only night measurements (21:00 – 07:00) were included. Substantial improvement can be seen in case of renovation in Building 1 where the average night-time concentration dropped from 3312 ppm down to 1471 ppm. The CO_2 concentration remains higher than recommended for the entire night due to high occupancy (this bedroom sleeps two adults and 1 child). However, the extreme concentrations above 2000 ppm were mitigated by the ventilation system. Also, in Building 3 the improvement is significant as the CO_2 concentration dropped from 1141 ppm in average to 743 ppm.

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[3] M Kotol, C Rode, G Clausen, TR Nielsen.Indoor environment in bedrooms in 79 Greenlandic households,Build.Environ. 81(2014) 29-36.

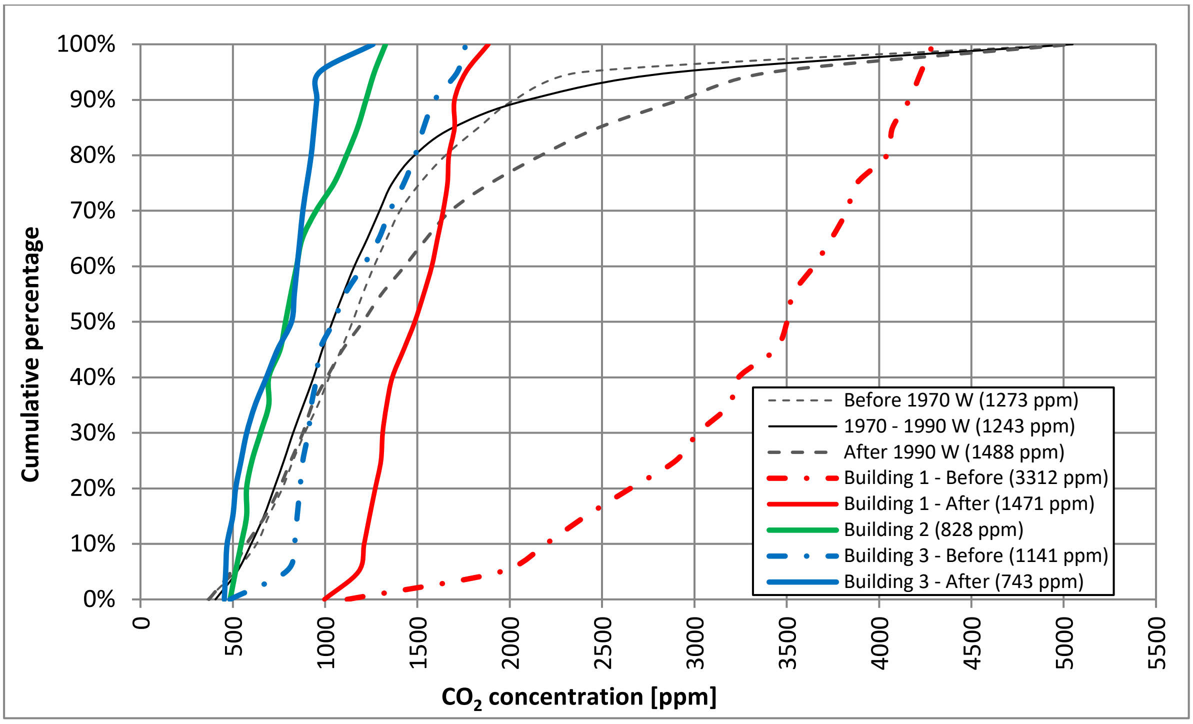

Figure 28 - Cumulative percentage distribution of CO_2 concentrations in the bedrooms during night-time compared with results of our previous study. The round brackets show arithmetic average.

Highest RH peak levels in the home are typically reached in bathrooms as the room volume is relatively small and the generation of moisture is large during bathing. Figure 11 shows two shower events that were captured in Building 1 before and after renovation. From the graph one can see that although the RH peaks at higher level in situation after the ventilation unit was installed (80% versus 73%) it only takes 27 minutes before the RH falls down to a recommended range. In the situation before renovation the RH remains above 50% for nearly 2 hours.

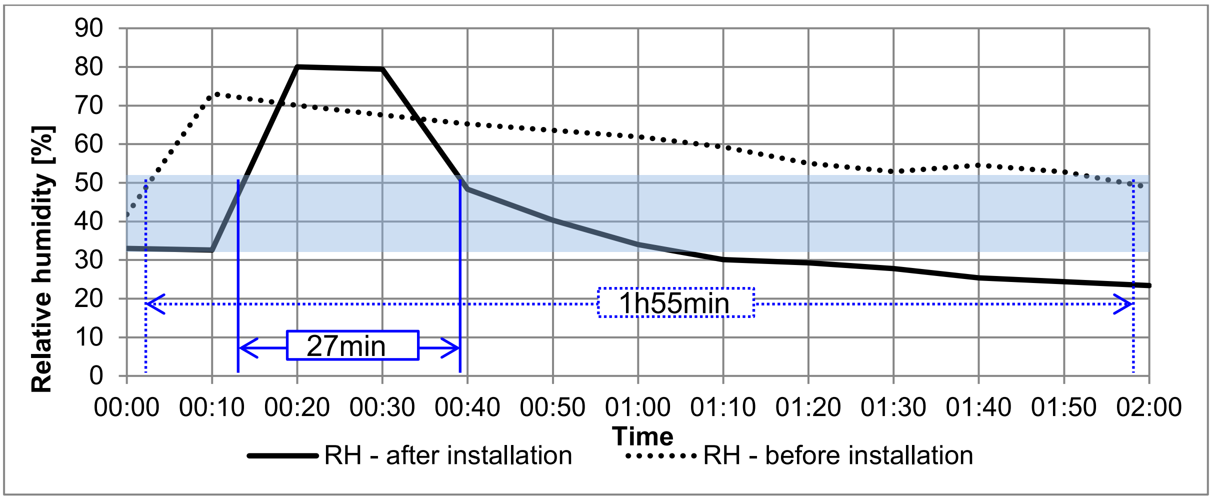

Figure 29 - Building 1 - RH at shower events before and after installation

The ventilation units used in Building 1 and 2 are equipped with a rotary heat exchanger and electric heater (500 W) to ensure that the supply air is at comfortable temperature. Both units were set identically to provide supply air at no less than 18 °C. This strategy reduces the risk of great discomfort at occupants. However, the temperature of the supply air provided by the decentralized ventilation unit used in Building 3 varies significantly as shown in Figure 30.

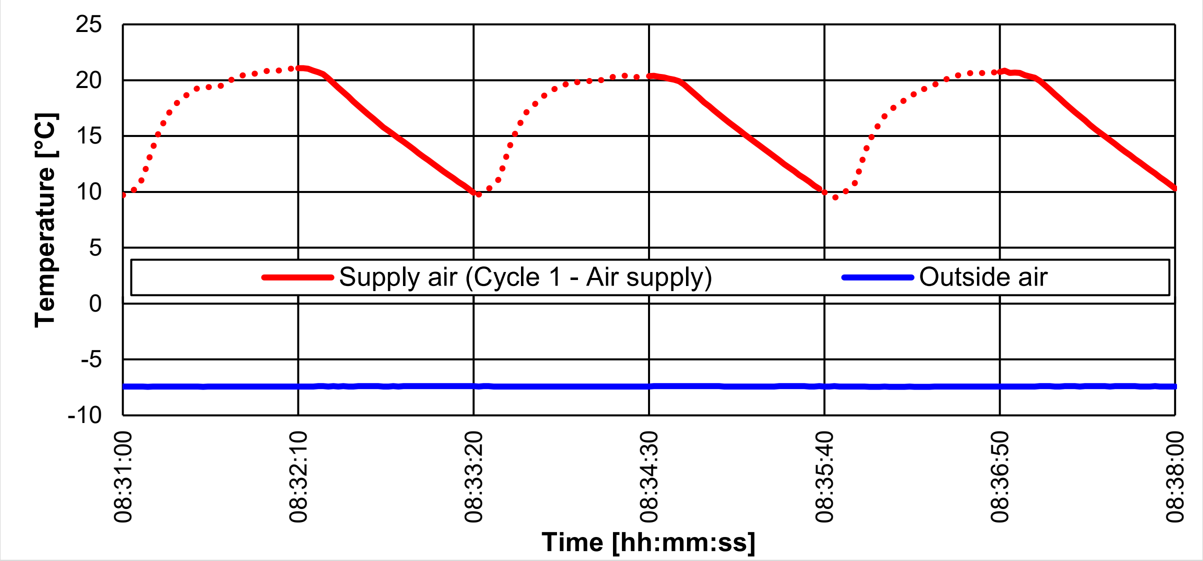

Figure 30 - Supply air temperature in the decentralized ventilation unit.

This variation is caused by the nature of the device and its construction where the cold air is heated by the preheated ceramic element. As the temperature of the element drops, so does it’s ability to heat the supply air.

When interviewing the occupants, in all three cases they expressed satisfaction with the quality of the air. In case of Building 1 the improvement was noticeable by both adults and kids. The occupants could tell that the stale air and odours from cooking, clothes drying, and other everyday activities were significantly reduced. When the adults were asked about the sound levels, a minor complaint was raised towards the noise of the system at highest speed which are used rarely. The ease of changing the filters was appreciated as the users would do this frequently due to allergic child. Another criticism was addressed to the space the installation takes in already rather small home.

The occupants of Building 2 did not have a chance to experience the before/after situation like the others. However, they could notice the difference in morning tiredness levels being less intense than they were used to. The absence of “bathroom switch” that would switch the unit into “Boost” mode either manually or automatically was criticized as the users had seen such one in the building 1 case and thought it was good in removing the bathroom moisture faster at shower events. This was mostly evaluated by the speed at which the mirror defogs. The first and largest concern of the occupants in Building 3 was toward the noise. The continuous switching of the fan directions and getting back to speed was found disturbing and eventually led to switching the system off for the nights. Additional concerns were about the supply air temperature. The occupants found the supply air temperature too low especially during windy periods.

5. Main conclusions and recommendations

- New envelope systems for Greenlandic climates were evaluated. CLT wall (which is not used in Greenland commonly) showed some good promise due to its good moisture handling, thermal properties, speed of construction and structural stability. The most significant drawbacks are transportation and material costs. The more common wall types were also found suitable after some adjustments were made (mostly insulation thickness).
- Heating and ventilation systems were studied, tested and evaluated. Hot air heating was found suitable for buildings with very low heating demand and only when high efficiency heat recovery is used. The main motivation for hot air heating is twosome: 1) Lower investment costs and 2) Coupling ventilation and heating leads to sufficient air change (better air quality) because reducing the air flow will lead to reduced temperatures hence greater thermal discomfort in occupants.
- We found that centralized mechanical ventilation systems with rotary heat exchangers perform flawlessly and can provide the occupants with sufficient air change without compromising thermal comfort. Unfortunately, these systems are often ruled out of the projects for economic reasons.
- The decentralized local ventilation units were found unsuitable for the Arctic climate due to great thermal and acoustical discomfort, low heat recovery efficiency and poor performance in windy conditions.
- Throughout the project, we realized that the occupants are often unaware of the principles and functionality of their HVAC systems, which leads to substantial heat losses. Similarly, systems that are frequently incorrectly installed, regulated or poorly maintained crave higher energy use. By educating the users, installers and by establishing regular service routines we can reach significant energy savings without large additional investment into renovations.

6. Further studies

Based on the research findings and experience gained throughout this project, the following topics should be investigated further:

- **Desiccant energy recovery wheels in small ventilation units**. It was found in this (and other projects) that the relative humidity in properly ventilated homes in the Arctic is very low. Reintroducing some of the extracted moisture appears to be beneficial for the IAQ. Doing it through energy recovery (or enthalpy) wheels is a strategy that we believe is worth testing.
- **Heat pumps**. Despite the original plan of this project, it was not possible to investigate the efficiency and optimal setup of heat pump systems. Their performance in the Arctic possibly in combination with other sustainable heat sources (such as solar systems) remains to be studied in the future.
- **Detailed energy use.** In order to be able to efficiently optimize and reduce the energy consumption of buildings, better understanding of the user habits in the Arctic is needed. It is therefore desirable to map the energy consumption and its distribution among individual systems (space heating, ventilation, lighting, household appliances, domestic hot water).