Passive house construction above the Arctic Circle

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Abstract. In Tuolluvaara, just outside Kiruna in northern Sweden, NCC has worked with Kiruna Municipality and Tekniska Verken i Kiruna AB to build the passive house project “Sjunde Huset”, a full-scale demonstration of a low-energy semi-detached dwelling for a sub-arctic climate. Based on NCC’s Cube concept for energy-efficient houses, the semis are built to FEBY12’s passive house criteria. The building serves as a test bed for the design, material choices, technical solutions and construction processes associated with energy-efficient construction in a sub-arctic climate. Features include a system for mechanical ventilation with heat recovery (MVHR). The building project has been prompted by the major social changes taking place in Kiruna and Gällivare and the newly tightened EU directives on energy consumption. This article presents the building and its energy-efficient solutions, along with measurements of the buildings heat loss factor (HLF), the ventilation system’s efficiency, and the specific energy consumption. We can report that Sjunde Huset meets FEBY12’s passive house requirements and that it is perfectly possible to build low-energy homes in a sub-arctic climate, with the potential to reproduce it at a lower production cost.

Keywords: Energy-efficiency, Near-zero energy, Passive house, Sub-arctic.

1 Background

The EU directive aimed at increasing the proportion of near-zero energy buildings (Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings) [1] states that such buildings must have an extremely high level of energy performance. Another requirement is that much of the small amount of energy that is supplied to these buildings should be from renewable sources, including renewable energy on-site or from the local vicinity.

Finding economically viable total solutions for whole areas and urban districts will be an important factor in fulfilling increasingly tough energy performance criteria. At the same time it is important not to ignore other aspects of sustainability such as making the areas attractive to live in and spend time in.

The major social changes that are taking place in Kiruna and Gällivare and the newly tightened EU directives on energy consumption provide a unique opportunity to get things right from the beginning and create a new society that is sustainable and attractive. Though, the conditions for building in a sub-arctic climate are challenging.

This article presents a full-scale demonstration of a low-energy house, “Sjunde Huset” (Seventh House), for a sub-arctic climate, one that serves as a test bed for the design, material choices, technical solutions and construction processes associated with energy-efficient construction in a sub-arctic climate. It showcases the building and its energy-efficient solutions, along with the results of measurements to ascertain the buildings heat loss factor, ventilation system’s efficiency and specific energy consumption. A more detailed description of the building Sjunde Huset, its technology, metrics, experiences from the production phase and feedback from the tenants can be found in the report Dehlin et al. (2017), published by the Swedish Energy Agency [2].

2 Sjunde Huset

2.1 Sjunde Huset as a passive house

Sjunde Huset (Seventh House), as shown in Fig. 1, is a passive house that took NCC’s “Cube concept” for cost and energy-efficient houses as the basis for its planning and construction. The Swedish definition for passive houses was formulated by Forum for energy efficient buildings (FEBY) based on the German definition [3]. However adjusted to generally used standards in Sweden slightly influence energy calculation results [4]. NCC puts the development and production costs at around 70% more than for a regular Cube house. One goal was for the building to be prefabricated as elements that could be assembled on-site, since conventional construction methods are not applicable. BASTA-approved materials have been used where possible.

Fig. 1. Sjunde Huset (Photo: Joanna Redman)

The building is located in Tuolluvaara, which will be part of the new Kiruna, in northern Sweden. The climate is classed as sub-arctic, with long, cold winters and short, mild summers. By November 2014, Sjunde Huset was completed and ready to be lived in.

2.2 Energy efficiency measures

Building envelope

To create an energy-efficient house, heat losses through the building envelope have to be minimized, which in practice means a building design that is compact and a building envelope that is well-insulated and airtight, with few thermal bridges. A highly efficient ventilation system with a high level of heat recovery is also required to minimize heat losses and keep the need for heating very low.

The timber-framed building comprises two semi-detached apartments, each with a floor space of 140 square meters. Apartments 1 (left) and 2 (right) have the same basic features: First floor containing the kitchen, living room that can be sectioned off to form an extra bedroom, laundry room, and toilet and shower. Second floor containing one large and two smaller bedrooms, toilet and shower, a family room that could be sectioned off to create another bedroom, and a walk-in closet.

The design of the house and its location on the plot has been adapted to the subarctic climate in order to reduce heat losses through the building envelope. The building has a compact shape that avoids angles in the facade to minimize the potential for thermal bridges. To reduce the ability for cold air to enter the apartments, porches have been built onto the entrances, forming airlocks between inside and out. This space is not heated and has walls with a “low standard of insulation”. The foundation slab is insulated from the building so that it is not a thermal bridge, and it is designed to minimize the risk of frost heave. There is also a storeroom and a carport outside the “warm shell”. The balcony is a freestanding structure to avoid thermal bridges.

The windows and doors have low thermal transmittance (U-value), 0.65 W/m^2K and 0.7 W/m^2K. The outer walls have additional rigid polyiso foam (PIR) insulation, which is an efficient, high-performance (0.023 W/m^2K) insulation material. The roof is insulated with 1000 mm loose-fill wool insulation. The foundation slab is insulated with 400 mm graphite foam. The average thermal transmittance for the building envelope, U_m (insulation value), is less than 0.16 W/m^2K, whereas the Swedish building standards require a value of 0.40 W/m^2K.

Ensuring that the insulated structure is airtight is important for various reasons. Air permeability reduces the infiltration of cold air, which causes drafts and increases the need for heating, and the exfiltration of air out of the building. It is important to minimize exfiltration in order to avoid the damp problems that can occur when warm, moist indoor air cools down inside the wall and forms condensation.

Green roof and stormwater management

The building has a gently sloping roof (< 6°) covered with moss/sedum/grass. There are numerous benefits to this type of roof: the sedum roof has an insulating effect (the soil layer is thermally dense), absorbs air pollution and reduces stormwater run-off. Sjunde Huset is testing two different types of sedum roof (sedum and sedum-herb) to see which kind is most effective in managing stormwater – which roof is best at absorbing rain, meltwater and water pollution – test carried out by LTU, see e.g. [5]. Alongside the sedum roof, which reduces the risk of large flows, there are also swales and soakaways in the ground. Stormwater is thus managed locally within the plot.

Solar panels

Each apartment is equipped with 15 m^2 solar panels. In climates with low sun and large amounts of snow, solar panels provide valuable additional energy even during the winter. To optimize their use in the winter, the solar panels have been placed on the facades rather than on the roof. In this position, reflected light from the snow can also drive up the production of electricity. During the summer, with its long period of midnight sun, electricity production will be substantial, of around 500 kWh/year from the solar panels, which have an estimated total production of around 900 kWh/year.

District heating

The homes are heated via a local heating system that in turn is heated by the municipal district heating system. The heating system is fueled by burnable waste from households and industry and leftover heat from the LKAB mining factory. The heat is distributed within the homes by an airborne heating system. The district heating is fed directly into the ventilation unit's ”heating” battery and into the washing machine, tumble dryer and dishwasher. The district heating network is laid together with the water and sewage pipes. The district heating was also used to thaw the ground before construction work began and to heat the site offices. This brought down electricity use in the production phase.

Ventilation system

The homes each have their own ventilation system (UNI3 from Flexit), with heat recovery and they are placed in the walk-in closet on the upper floor. The unit has a rotating heat exchanger and a heating battery that is connected to the district heating network. The air is distributed to the bedrooms and family room through valves placed at ceiling height. The extract air is placed in the kitchen, bathroom and laundry. In addition to the task of supplying the homes with new clean air, the ventilation system also has to meet the heating needs in the building. Since the heating is provided through the ventilation system, there are no radiators in the rooms.

The airtight building envelope ensures the optimal operation of the ventilation system, which recovers the heat from the extract air, reduces heat leakage and removes cold drafts. The MVHR unit has a high-performance heat exchanger – 83% at a design winter outdoor temperature (DVUT) of -30°C according to the supplier's specification. District heating supplies the heating battery, as well as the washing machine, tumble dryer and dishwasher.

The ventilation unit has three operational flows: high and low speed plus a booster setting that only runs for 30 minutes. The default for the ventilation unit is high speed, which has been designed and calibrated as 55 l/sec (0.4 l/s, m² A_{temp} (A_{temp} – interior area that is heated)). A site visit in November 2016 revealed that the right-hand apartment 2 had the flow set at low speed, probably ever since it was handed over. Low speed equates to a flow of around 40 l/s. The supply air temperature is controlled by the desired temperature in the room, which is measured in the extract air.

The ventilation unit has a built-in defrosting function. This function needs to be activated manually, but this rarely happens, since problems of frosting are rare in units with rotating heat exchangers. The risk is greater in Sjunde Huset, due to the subarctic climate. However, the defrosting function appears not to have been activated for any of the building's units.

White goods and lighting

Sjunde Huset has been fitted with low-energy white goods and lighting in order to further reduce the demand for energy. The white goods are connected to the district heating, which is expected to cut electricity demand by 80%. Since Kiruna has a long period of darkness with polar nights, the homes have been equipped with various types of facade and outdoor lighting. All use LEDs, which is expected to bring a saving of up to 80% for the same light strength, compared with regular filament bulbs.

Co-location of district heating with water and sewage pipes

The residential area in which Sjunde Huset is located has special infrastructure for water, wastewater and district heating. A low-temperature district heating network has been laid together with the water and sewage pipes, which are warmed by the heat given off. Placing all the pipes together makes it possible to bury them at a depth of just 70 centimeters. Normally in Kiruna, they would have to be dug down 3 meters to remain frost-free. Since Kiruna is built on bedrock, this dramatically reduces the cost of running the pipes. Further studies into co-location of pipes are set to be conducted and reported via the cross-disciplinary project Attract [5].

Showers

Instead of a conventional shower system, Sjunde Huset is fitted with energy-smart water-recycling showers from Orbital. These showers use technology developed by NASA to clean and re-use the water: Water that runs into the drain is collected, filtered and pumped back up to the shower head, allowing the same water to be used again and again. The integral water treatment unit filters out particles, bacteria and viruses. The water is only flushed away once the shower is over. With this system, a ten-minute shower uses only five liters of water. The water loses about two degrees in temperature from the shower head to the drain, so it needs to be reheated by an electric heater that is part of the shower system. Electric heaters in showers meet the energy requirement, but may require special dispensation within the Swedish building regulations in order not to affect the passive house certification.

Display

The apartments in the Sjunde Huset building are equipped with displays in the hall plus temperature sensors in all the rooms. This makes it easy for residents to keep an eye on their use of hot water and energy. The hall also has a central control switch that turns off all the lights in the house in one go.

3 Measurements and analysis

The aim of building Sjunde Huset has been to show that despite its sub-arctic location, it is possible to build a low-energy house that still meets the Swedish standards for passive houses. Sjunde Huset is built to FEBY12's passive house criteria for the conditions of Climate Zone I [1]. The criteria include requirements concerning specific energy consumption and the buildings heat loss factor. Since the standard for specific energy consumption is high, the ventilation needs to perform extremely well.

The heat loss factor is a measure of the heat that leaks out from the building when it is coldest outdoors, and the criteria for compliance depend on where in the country the building is located and what type of heating system exists. For Sjunde Huset, the heat loss figure must be no higher than 19.8 W/m^2 A_{temp}. According to FEBY12, the building's specific energy consumption $Es_{upplied}$ must not exceed 63 kWh/m^2 A_{temp}/year, since the building is classed as not electrically heated. Air leakage q50 through the building envelope must be no more than 0.30 l/s per m^2 of enclosed area at a pressure difference of 50 Pa.

3.1 Measurements conditions and deviations

The measurement values for temperatures and air humidity in the ventilation units and in various rooms used for the technical analysis and later also for the production of the heat loss factor figures are average values on a 15-minute basis. This is because the minute by minute data produced files that were too large to handle.

The system efficiency has been calculated on an annual basis (January 1, 2016 to February 20, 2017), but also for the period October 2016 to February 2017, which is part of the heating season. This is to see how performance differs between the heating season and on an annual basis, expecting the efficiency to be slightly higher.

There is a meter to measure the heat supplied to the heating battery in the unit, which has been monitored and compared with the calculated energy consumption in the battery. Sensors from the manufacturer Regin have been installed in the ventilation unit to log temperatures at five points. The five sensors measure the temperature of the outdoor air, supply air (before the heating battery), supply air (after the heating battery), extract air and in the exhaust air. In addition to temperatures, the sensors also measure relative humidity at these points. Key limitations and deviations in the input data and conditions that affect the measurements:

- Collection of measurement data during the time periods January 1 to April 30, 2016 and August 20, 2016 to February 20, 2017 due to router problems: problems transferring measurement data to the database and overwritten measurement data.
- Purchase of incorrect sensors for the ventilation units' exhaust air that can only measure temperatures in the range 0-50°C. All minus temperatures have been recorded as 0°C. When calculating system efficiency, the temperature of the supply air has been used instead.
- The substation that Tekniska Verken, the district heating supplier in Kiruna, owns has long had a factory-controlled night reduction that was not known. This means that at night the heating battery for the ventilation has not been able to deliver the necessary quantity of heating, which in turn has led to a substantial drop in the indoor temperature. The night reduction function was removed November 22, 2016.
- The tenants have not had the apartments as their permanent residence, which means that they have been used considerably less than was planned and expected.

3.2 Calculation conditions Heating battery energy consumption

Energy consumption in the battery has been calculated using measured temperatures and produced with the help of the following formula:

$$Q_{Battery} = \sum_{i=1}^{i=n} \rho \;\; C_p \;\; q \;\; \left(T_{supply\ air,i} - T_{hr,i}\right) \tag{1}$$

$Q_{Battery}$	Battery energy consumption [kWh]
ρ	Air density, 1.2 kg/m^3
C_p	Specific thermal capacity, 1 kJ/kgK
q	Air flow [m^3/h]
$T_{supply\ air,I}$	Supply air at each 15-minute value
$T_{hr,i}$	Temperature after heat recovery at each 15-minute value

3.3 Calculation conditions for the heat loss factor

The following formula has been used to calculate the heat loss factor (HLF) using measurements from the building:

$$\mathrm{HLF_{WDT}} = \mathrm{H_T}\;\; (21 - \mathrm{WDT})\;/\mathrm{A_{temp}} \tag{2}$$

H_T is the building's heat loss coefficient [W/K] and WDT is the design winter outdoor temperature for the location in question. To determine the heat loss factor, WDT is chosen for a time constant of max 12 days, which equates to -24.3°C. If you choose a time constant of just one day, the WDT instead becomes -30.3°C. The thermal loss coefficient has been calculated for a time constant of both 1 day and 12 days to see how the two differ. H_T is produced from the formula:

$$\mathrm{H_T} = \mathrm{U_m}\;\; \mathrm{A_{encl}} + \rho\;\; \mathrm{C_p}\;\; \mathrm{q_{leak}} + \rho\;\; \mathrm{C_p}\;\; \mathrm{d}\;\; \mathrm{q_{vent}} \cdot (1 - \eta) \tag{3}$$

U_m	The building envelope's average U-value
A_{encl}	The building envelope's enclosed area, measured internally
$\rho \;\; C_p \;\; q_{leak}$	Thermal energy losses due to air leakage q_{leak} [m^3/s], air density ρ [kg/m^3], and thermal capacity C_p [kJ/kg,K]
$\rho \;\; C_p \;\; q_{vent}\ (1-\eta) \;\; d$	Thermal energy losses due to ventilation with regard to the system's efficiency, η, density, ρ, thermal capacity, C_p, relative operating time, *d*

The calculation of air leakage, q_{leak}, for an MVHR system takes account of the building's location and balancing of the ventilation, in line with EN ISO 13789:2008:

$$\mathrm{q_{leak}} = \mathrm{q_{50}} \cdot \mathrm{A_{encl}} \cdot \mathrm{e} \;/\; (1 + \mathrm{f/e}\; ((\mathrm{q_{supl}} - \mathrm{q_{extr}})/\; \mathrm{q_{50}} \cdot \mathrm{A_{encl}})^2\,) \tag{4}$$

$q_{supl} - q_{extr}$	Air surplus between supply air and extract air [l/s]
q50	Leak flow at 50 Pa pressure difference between inside and out [m^3/s].
e and f	Tabulated wind protection coefficients

Since the flow of the ventilation is balanced, $q_{supl} - q_{extr}$ becomes 0, such that the simplified equation becomes:

$$\mathrm{q_{leak}} = \mathrm{q_{50}} \cdot \mathrm{A_{encl}} \cdot \mathrm{e} \tag{5}$$

3.4 Calculation conditions Specific energy consumption

The requirement concerning specific energy consumption, $E_{supplied}$, includes purchased energy for heating, hot water and the building's installations (fans and pumps).

$$E_{supplied} = E_{heating} + E_{domestic\ electricity} + E_{hot\ water} \tag{6}$$

The "NASA" showers with their recycled hot water contain a small electric battery, which technically means this is a "non-pure system that is heated with both electricity and district heating". However, since the electric batteries are "extremely limited" in scope, the building is instead classed as having a "pure heating system", with a FEBY12 requirement of 63 kWh/m² A_{temp}/year that must not be exceeded.

3.5 Measurement results

Below are the results from the calculations made using the above conditions. For a more detailed description and more graphs, see report Dehlin et al. (2017) [2].

Ventilation system efficiency

The average system efficiency on an annual basis comes out at 81% for the unit in apartment 1 and 79% for the unit in apartment 2. Relating the system efficiency to the outdoor temperature reveals that the heat exchanger is most stable when it is cold outside. When the weather is warmer, the results show a broader spread: System efficiency approaches 100% when the temperature outside is the same as the desired temperature inside. The efficiency approaches 0% when the outdoor air temperature is higher than the supply air temperature, which gives a low efficiency figure in the calculations, sometimes even negative.

Fig. 2 shows the graph for system efficiency in both units during the "heating period" from October 1, 2016 until February 20, 2017 (plotted as daily averages for clarity). The figure for average efficiency during this period is 81% for the unit in apartment 1 and 80% for apartment 2.

At the start of the period, the system efficiency for the two units differs somewhat. The efficiency of the unit in apartment 1 is higher than the efficiency of the unit in apartment 2. One explanation may be that the intake duct for apartment 1 faces south, so the effect of the sun is greater here than for apartment 2 (north-facing).

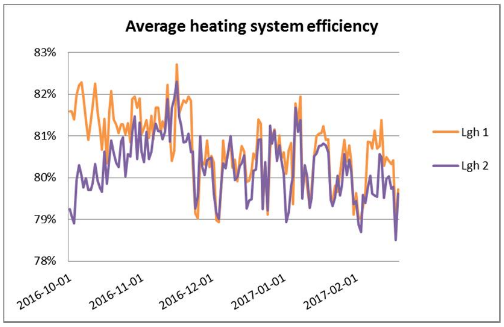

Fig. 2. Average heating system efficiency per day during the heating season

Battery energy consumption

See Table 1: In apartment 1, the battery used 4482 kWh between October 1, 2016 and February 20, 2017 and in apartment 2 the corresponding figure is 4016 kWh. These figures are taken from the heat supply meter and relate to the period October 1, 2016 and February 20, 2017, not the whole heating season. Since the apartments are identical, the measured energy demand should be the same, but in fact they differ by almost 500 kWh. A logical explanation for the lower energy use in apartment 2 is that the air flow was lower for a time; see section “Measurements conditions and deviations”.

Table 1. Measured and estimated energy in heat exchanger and battery

	Apartment 1 [kWh]	Apartment 2 [kWh]
Measured energy battery	4482	4016
Estimated energy battery	3909	4026
Estimated recovered energy exchanger	5030	4454
Estimated energy demand without exchanger	8939	8480

In apartment 1, the heat exchanger recovered 56% of the energy during the stated period, while in apartment 2 the heat exchanger recovered 53% during same period.

Heat loss factor

Table 2 presents the results of the heat loss factor for both WDTmin (-24.3°C) and WDTmax (-30.3°C). As clearly shown in the table, the heat loss factor is well below the requirement set by FEBY12 of 19.8 W/m^{2}Atemp. The heat loss factor, calculated at an early stage and for a time constant of 12 days, equating to WDTmax, also works out at 16.3 W/m^2, which means that there is a good match between the measured value and the estimated value.

Table 2. Heat loss figures for Sjunde Huset

	HLF_{WDTmin}	HLF_{WDTmax}
Apartment 1	14.20	16.10
Apartment 2	14.30	16.20
Whole building	14.20	16.10

Specific energy consumption

Measured values for calculating specific energy consumption for the period July 15, 2015 to July 15, 2016 were produced by Daniel Risberg at LTU. However, these values are not used in their pure form. They are adapted to deviations relating to low use, low indoor temperature and high outdoor temperature (compared with a normal year).

Estimated specific energy consumption, $E_{supplied}$, is 56.7 kWh/m²/year, which is well within FEBY12’s passive house requirement of 63 kWh/m² A_{temp}/year.

Air permeability

Air permeability tests were performed in September 2014. The left and right apartments were tested separately. The test was carried out in line with standard EN-13829 *Thermal performance of buildings.*

The calculated air permeability of the total enclosed area ranged between 0.23 and 0.27 l/s m², and the project's agreed air permeability requirement was 0.31 l/s m². Both the apartments meet the air permeability requirement of 0.31 l/s m² within a 10% margin of error, irrespective of whether the party wall separating the apartments is included in the area calculation.

4 Conclusions

The full-scale demonstration building, constructed to FEBY12's passive house criteria for the conditions of Climate Zone I, has definitely helped to increase our knowledge of low-energy houses and innovative new technical solutions.

This article presents the building and its energy-efficient solutions, along with the results of measurements of the ventilation system's efficiency, the heat loss factor and specific energy consumption. Measurements have been affected by certain issues, e.g. sporadic occupancy, purchase of the wrong sensors and various operational problems. We can still report that Sjunde Huset meets FEBY12's passive house requirements and that it is perfectly possible to build low-energy homes in a sub-arctic climate.

We can also draw a number of important and well-founded conclusions about the heat recovery system, based on measurements and feedback from the tenants: The heat recovery system requires particularly intensive upkeep, with regular calibration of air flows, maintenance – such as duct cleaning and filter replacement – and switching between summer and winter settings in order to deliver good comfort and a pleasant indoor environment. The heat recovery ventilation system (supply/extract air units in the ceiling, extract air units in the wetrooms and kitchen) leads to a certain degree of uneven temperature distribution in the house – colder on the lower floor than on the upper floor – along with cold floors and a dry indoor climate.

The starting point for the development of Sjunde Huset was NCC's Cube concept house, which was upgraded to a passive house. Having created a passive house concept for Kiruna's conditions, there is now the potential to reproduce it at a lower production cost. Future houses will also cost less to live in due to their low energy consumption. A functional and sustainable passive house concept should now be an attractive alternative for newbuild housing in Kiruna.

5 References

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