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Article

Energy and Environmental Performance of Multi-Story Apartment Buildings Built in Timber Construction Using Passive House Principles

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Abstract: This paper presents energy and environmental performance analyses, a study of summer indoor temperatures and occupant behavior for an eight story apartment building, with the goal to combine high energy efficiency with low environmental impact, at a reasonable cost. Southern Portvakten building is built with prefabricated timber elements using passive house principles in the North European climate. Energy performance was analyzed through parametric studies, as well as monitored energy data, and complemented with analysis of occupant behavior during one year. Results show that airtight, low-energy apartment buildings can be successfully built with prefabricated timber elements in a cold climate. The monitored total energy use was 47.6 kWh/m^2, excluding household electricity (revised to a normal year), which is considerably lower than of a standard building built today in Sweden—90 kWh/m^2. However, the occupancy level was low during the analyzed year, which affects the energy use compared to if the building had been fully occupied. Environmental analysis shows that the future challenges lie in lowering the household and common electricity use, as well as in improving the choices of materials. More focus should also lie on improving occupant behavior and finding smart solar shading solutions for apartment buildings.

Keywords: massive timber; multi-story building; energy use; environmental performance; prefabricated elements; low energy building; new construction

1. Introduction

The recast of the Energy Performance of Buildings Directive (EPBD), adopted by the European Parliament in May 2010, sets new targets for building energy efficient buildings [1]. It is a result of the tight goals set by the European Community to combat climate change and reduce the total energy use and environmental impact from the building sector [2]. For many years, low energy buildings have been built across Europe and evaluated by the property and research sectors. Lessons learnt from the first passive house residential building, completed 20 years ago in Germany [3], have served as a basis for further development of energy efficient buildings, and since then, thousands of passive houses have been built around the world, but mostly in central Europe.

In Sweden, voluntary passive house criteria have been developed by FEBY (Forum for Energy Efficient Buildings) [4]. The criteria are based on the Passive House (PH) criteria developed by the Passive House Institute in Germany, but adapted to the Swedish building regulations and local climate conditions [5]. A summary of the voluntary Swedish Passive house criteria, version 2008:1, used during the project's development stage, is presented in Table 1.

Table 1. Summary of the key elements of the voluntary Swedish Passive House criteria, version 2008:1, residential buildings.

Requirements	Southern climate zone	Northern climate zone
Peak load for space heating	Maximum 10 W/m^2	Maximum 14 W/m^2
Detached houses <200 m^2	Maximum 12 W/m^2	Maximum 16 W/m^2
Recommendation for energy demand (space heating demand, domestic hot water and electricity for mechanical systems, as well as general electricity used by the building)	45 kWh/m^{2}a	55 kWh/m^{2}a
Detached houses <200 m^2	55 kWh/m^{2}a	65 kWh/m^{2}a
Mechanical ventilation	0.35 L/(s m^2)	
Sound from the ventilation system	Minimum class B	
Airtightness	0.3 L/(s m^2) at +/− 50 Pa	
Windows and glazed areas	Average maximum 0.9 W/m^{2}K	
Free heat from household appliances, people and solar gains, to be accounted in the peak load calculations	Max 4 W/m^2	
Set indoor temperature for calculations	20 °C	
The outside temperature used for peak heat load calculations (DUT)	Calculated for the location according to the Swedish standard, SS024310	
Supply air temperature	Maximum 52 °C in each supply air device	

The research object, Southern Portvakten in Växjö, is the first of its kind in Sweden, where timber as a construction material is combined with passive house principles for good energy performance in a

high rise apartment building, eight stories high. In 1994, fire regulations for buildings in Sweden changed to being based on functional demands rather than on material demands, which was thanks to the changes in the European Directive for Building Products (89/106/EEC, with amendments 93/68/EEC) [6]. Besides low energy use, it was expected that by choosing timber as the construction material, the total environmental impact would be lower than from other low energy buildings built using other conventional materials for construction. Application of solid timber constructions is rare in high rise buildings. In the UK, a nine story-high apartment building was constructed in prefabricated cross laminated timber elements in 2009 [7,8]. Even though the base cost of the timber construction was 10% to 20% more than of comparable reinforced concrete, the savings are seen in 30% reduced erection time, no need for storage on-site, which saves space and reduces on-site waste, and high repetition rate that provides for improved safety [9]. The CO_2 stored in the construction corresponds to the CO_2 emissions of 20 years of building operation [7], but the saving could have been even greater if the building was constructed as a low energy building.

This paper presents an analysis of the energy and environmental performance of the research object, in comparison with if it was built using the technical system solutions of a reference building, Limnologen (95 kWh/m^{2}a), built according to the local energy requirements, and if it was built as a conventional building, according to the Swedish national regulations issued in 1993, with changes in 2008, regarding building's energy performance (110 kWh/m^{2}a) [10].

2. Description of the Building

The research object, Southern Portvakten, situated in Växjö in southeast Sweden, is a pioneer project combining a load bearing system of mainly timber with passive house principles in a high rise building to achieve both low energy use and environmental impact. It is one of the two eight story high buildings that were designed and erected during 2006–2009. Both buildings have identical design of the building's envelope and structure and technical systems.

2.1. Building Envelope and Structure

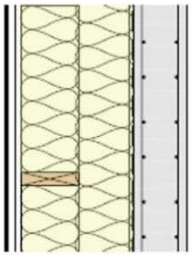
Even if timber is the main load bearing material, the ground floor of the building, including structural elements as walls, slab-on-ground and the first intermediate floor are constructed in concrete *in situ*, mainly due to economic reasons and stability. All other floors are constructed with prefabricated timber elements, including the elevator shaft and the staircase area.

The exterior walls have a U-value of 0.11 W/m^{2}K (including 13% of thermal bridges of the whole surface of the exterior walls), achieved by using 385 mm of insulation (mineral wool) in prefabricated timber wall elements and 390 mm of insulation (mineral wool) that covers the concrete walls of the ground floor. A cross section of the outer walls can be seen in Figure 1 [11].

Figure 1. Cross section of the outer wall elements, with concrete-bearing wall at the ground floor and the timber-bearing wall at all upper floors.

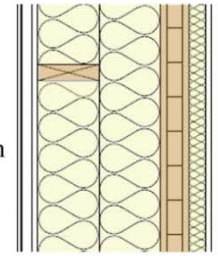
Ground floor outer wall

Cement fibre panel 8 mm
Sealing joint 2 mm
Wooden bolt 28*45 mm
Gypsum board 17 mm
Horizontal wooden stud 45*195 mm
Insulation (mineral wool) 195 mm
Vertical wooden stud 45*170 mm
Insulation (mineral wool)170 mm
Plastic foil
Concrete 180 mm



First to eight floor outer wall

Cement fibre panel 8 mm
Sealing joint 2 mm
Vertical wooden bolt 28*95 mm
Gypsum board 17 mm
Horizontal wooden stud 45*170 mm
Insulation (mineral wool)170 mm
Vertical wooden stud 45*170 mm
Insulation (mineral wool) 170 mm
Plastic foil
Massive timber
Vertical wooden bolt 45*45 mm
Insulation (mineral wool) 45 mm
Gypsum board, fire protective



The slab-on-ground is insulated with 300 mm of expanded polystyrene and has a U-value of 0.097 W/m^{2}K. The attic floor, of the unheated attic, has 500 mm of insulation and a U-value of 0.075 W/m^{2}K. All intermediate timber prefabricated floors have 170 mm of insulation (mineral wool) between the timber joists and an additional 70 mm of insulation (mineral wool) continuously below the joists and above the suspended ceiling. There is no insulation between the ground floor and the first floor. The roof is pitched in two sides, with inclinations of 40° towards the south and 15.6° towards the north. The roof construction is prepared for installing solar cells for electricity production, which, due to the costs, have not been installed.

All windows are operable, triple glazed, with krypton filling in both gaps between the glasses, one low-emissivity coating and one solar control glass coating. The windows have a light transmittance of approx. 54% and total solar energy transmittance of approx. 31%. There are no other sun shadings installed. The most common window size at Southern Portvakten is 988 × 1288 mm, with a U-value 0.98 W/m^{2}K, while the balcony doors have a total U-value of 1.08 W/m^{2}K. The high U-value of the windows can be explained by the large cost for specially produced, better performing windows on the Swedish market during the project's development stage. Due to an average U-value of the windows higher than 0.9 W/m^{2}K, the research object does not meet the voluntary criteria for passive houses in Sweden. A summary of the U-value of the building envelope and structure can be found in Table 2.

Table 2. Summary of the U-value of the building envelope and structure.

Heat transfer coefficient (U-value)	W/m^{2}K
Exterior wall	0.11
Roof (last intermediate floor towards the unheated attic)	0.075
Windows	0.98
Balcony doors	1.08
Slab-on-ground	0.097

Airtightness of the building's envelope was targeted to be 0.2 L/(s m^2), building envelope area at +/−50 Pa. Special attention was paid to developing good solutions for securing high airtightness of

outer wall elements, their connections and sealing around the windows and doors, due to the specifics of the construction material and prefabrication system used.

In an earlier study by Sherman and Chan [12], it was observed that in multi-story buildings, the major leakage sources in the exterior walls are found to be windows, balcony doors and vertical shafts, in descending order of importance. Windows were therefore installed in the exterior wall elements at the factory, and the sealing system was tested before installing the wall element at the construction site. The airtightness was controlled for the building elements, in a laboratory setting and in two blower door tests of the partial and the fully constructed building. The blower door test for the whole building gave an average of 0.19 L/(s m^2) at +/−50 Pa. Overall accuracy of the measured air leakage rate is estimated to be within ±10 percent.

2.2. Building Services

The mechanical ventilation system includes one double plate air-to-air heat exchanger for the whole building; the technical specification can be found in Table 3. The ventilation rates are dimensioned according to the volumes of the apartments, with the airflow ranging from 25 L/s (smaller apartment) to 28 L/s (larger apartment). The ventilation air flow in the staircase is 25 L/s.

Table 3. Description of the building services.

Building services	Description of the system
Double plate air-to-air heat exchanger	Heat recovery rate of 85% (temperature efficiency). Specific fan power of 1.27 kW/(m^3/s) at an air flow of 1 m^3/s and 200 Pa in channel pressure drop. Possible icing of the heat exchanger is prevented with a by-pass valve
Central heating battery	Heating power of 4.8 W/m^2, floor area, with hot water from the district heating system as the energy carrier
32 individual batteries (one in each apartment)	Heating power of 15.2 W/m^2, floor area, with hot water from the district heating system as the energy carrier
Domestic hot water	Connected to the district heating system
Waste water heat exchanger	Designed to recover 1000 to 1500 kWh/apartment per year, depending on number of occupants and living habits [13]

The building is connected to a district heating system, used for both domestic hot water (DHW) and space heating. The building's heating system consists of a central heating battery for the whole building and an individual supply air heating battery in every apartment for individual temperature regulation. All heating batteries are supplied with hot water from the district heating system. In total, the installed heating power in the building is 20 W/m^2, which is higher than recommended by the Swedish voluntary passive house criteria.

The building is connected to a waste water heat exchanger, which is also connected to waste water from the almost identical neighboring building.

3. Method and Limitations

3.1. Energy Performance Analysis

The energy performance analysis comprised of three parts. During the design stage, a parametric study was carried out through dynamic energy simulations conducted in DEROB-LTH (Dynamic Energy Response of Buildings) [14], where, e.g., the effect of window type and shading solution, the efficiency of the heat exchanger and level of airtightness was studied. After completion of the building, a comparison between calculated and monitored energy performance and summer indoor temperatures, including analysis based on occupancy level, was performed. For both parts, the studied parameters were peak heat load, space heating demand and summer indoor temperatures. Finally, experiences with installed building service systems were analyzed on the basis of their effect on the overall building's energy performance.

The simulation tool DEROB-LTH v2.0 (Dynamic Energy Response of Buildings) [15] was used to explore the complex dynamic behavior of the building for different options. The building model was divided into volumes that represent apartments and the building staircase, where, within the tool, the number of volumes is limited to eight [16]. Parametric studies were performed for three separate cases: the bottom floor, the middle floor and the top floor. Individual results of the models were then compiled and analyzed for the whole building. It was assumed that the middle floor could represent the 2nd–7th floor of the building. DEROB-LTH does not examine thermal bridges separately, so they need to be included as part of the description for each building element. Thermal bridges in the building envelope were calculated by the building element producer and the construction company and used as input for the simulations. The local climate data for the simulations were compiled from the database Meteonorm [17], where the closest available data of Jönköping airport was used.

Metering devices were installed to follow the energy performance of specific posts: energy needed for heating, domestic hot water (DHW), water circulation system and common electricity, on the level of the whole building. Each apartment was equipped with metering devices for measuring energy use for DHW, household electricity and indoor temperature. The monitoring was conducted by the building owner, and the research team was provided with adequate data. The measurement results were analyzed during the period of one year, starting three months after the building was set into operation and compared to the simulated energy performance. The first three months were not included in the analyses due to a number of adjustments of the building's technical system and low occupancy levels (see Table 4). In order to perform a valid comparison, both calculated and monitored energy performance results were normalized to a "normal" climatic year.

Indoor temperatures were analyzed for six apartments at different floors and orientation. It was interesting to examine the difference in indoor temperatures in apartments due to their orientation, floor level and changes in the outdoor temperatures, as well as exposure to solar radiation and risk for overheating during the summer months. For the assessment over the 12 month period, monthly average indoor air temperatures were used, due to the limitations of the monitoring devices to provide data in usable form for more frequent reading. However, summer indoor air temperatures were analyzed in more detail for two apartments, where highest indoor temperatures were expected, over a three month period, June, July and August. Daily average indoor air temperatures were used.

Table 4. Building's occupancy level (number of rented apartments) during the first 15 months. The first three months were not used for the analysis of the measurement data. Total number of apartments in the building is 32.

Month	Number of rented apartments	Month	Number of rented apartments
1	11	9	16
2	11	10	14
3	12	11	15
4	13	12	19
5	15	13	19
6	16	14	19
7	16	15	23
8	17	-	-

Estimated internal heat gains from people and appliances in relation to different occupancy levels are presented in Table 5. The energy simulations for different occupancy levels and their effect on the building's energy demand were carried out as a complementary analysis to the measured energy performance in order to investigate the influence of the low occupancy levels. A detailed analysis of internal heat gains was done for a fully occupied building (with average 1.8 people per apartment), a half occupied building (with average 0.9 people per apartment) and an empty building (no occupants), where basic appliances were in operation. The option with the empty building was used for comparison reasons. In reality, only the first month in operation, when the first inhabitants were moving in, the building had low occupancy level. In the future, it is not expected that such a situation would ever occur again. Parameters for internal heat gain analysis were acquired from earlier studies [18–23]. This was compared to the maximum recommended internal heat gains in the Swedish voluntary passive house criteria of 4W/m^2 [5]. Internal heat gains were identified as from people, household electricity (appliances and lighting), common electricity, heating distribution system and heat losses from the DHW circulation system.

Table 5. Internal heat gains used for energy simulations.

Source of internal heat gains		Fully occupied building	Half occupied building	Empty building
People (per apartment), W	Constant	84.6	42.3	0
Household electricity (per apartment and period of the year), W	November–March	164.5	136.4	54.1
	April–May	135.6	112.5	44.6
	June–August	108.7	90.1	35.8
	September–October	132	109.5	43.5
Common electricity (allocated to the staircase), W	Constant	136.4	136.4	136.4
Circulation losses from district heating and DHW system (allocated to all volumes, apartments and the staircase), W/m^2		0.3	0.2	0.2

3.2. Occupant Questionnaire

After one year in operation, a questionnaire was sent out to the inhabitants of the two Southern Portvakten buildings, the investigated building and the adjacent "twin" building. Due to the low occupancy levels, the questionnaire was sent out and analyzed for both buildings. The questionnaire was based on the Engvall/USK form Energy 02 [24].

3.3. Environmental Analysis

For the building's environmental performance analysis, the attributional LCA methodology was used, defined by its focus on describing the environmentally relevant physical flows to and from a lifecycle and its subsystems. The analysis had several boundaries: geographical for the production of the raw material (where Ecoinvent database in the GaBi professional database was used [25]), electricity (where Nordic average data were used [26]), district heating (where Swedish average data were used [26]) and time, which was set to 60 years and excludes the decommission time. The environmental analysis focused on primary energy (PE) use and global warming potential (GWP). The analysis of PE use includes energy system chains from natural resources to useful energy services [27] and shows the energy use by different posts during the building's production or operation stages and a comparison between the analyzed building options, where the potential consumption and savings are achieved. GWP, on the other hand, gives an assessment of the impact the buildings create to the environment equivalent to CO_2 emissions. The global warming and increasing emission of GHG, particularly CO_2, have become a major concern in the building industry and research community [28,29]. The time frame of 60 years was used with the assumption that the building should be used for at least 60 years, and the results could be compared with other research results. The analysis did not include possible building renovations, changes in electricity mix over the years or climate change that might have an effect on the building's energy need. These aspects would not have significant effect on the comparison results, while they would require many assumptions to be made (all the buildings used in the comparison will be renovated more or less in the same way during the 60 year period, and the energy mix would change for all the buildings in the same way, while it is difficult to predict how this would change from today's perspective). Also, decommissioning of the building is left outside the boundaries of the study, since it is difficult to predict how the decommissioning will be done in 60 years, which would be the same for all the building cases analyzed.

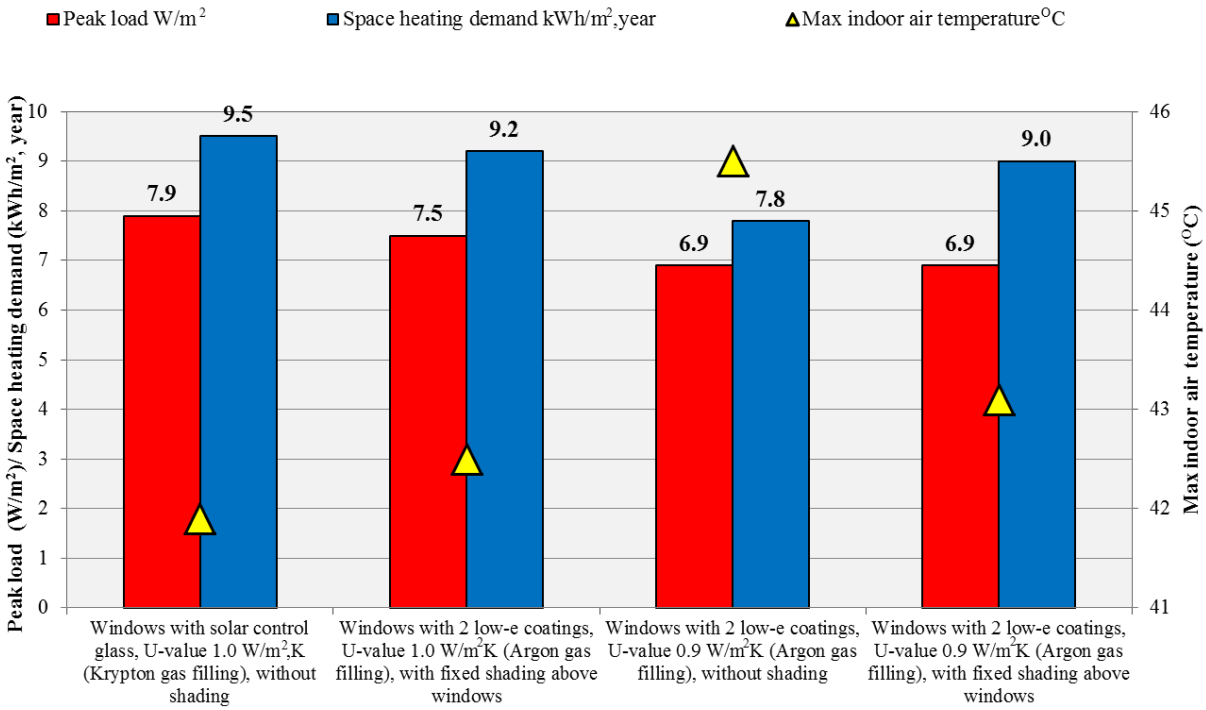
4. Results

4.1. Energy Performance Analysis

Window type, size, shading options, gas filling and U-value have an impact on the building's energy performance and indoor temperatures [30–33]. According to simulations, of four considered options, windows with solar control glass (final design solution) contribute to the best indoor climate, concerning indoor temperatures during the summer months, but at the same time, result in the highest space heating demand compared to the analyzed options (Figure 2). Better performing windows (with U-value 0.9 W/m^2K and without solar shading) provide better energy performance, resulting in almost

1 W/m^2 (13%) lower peak load and 1.7 kWh/m^2 (18%) less space heating demand, compared to the chosen solution with solar control glass, but result in 3.5 °C higher indoor temperature during the summer. Windows (U-value 0.9 W/m^{2}K and without solar control glass) with a fixed horizontal shading above the windows, 60 cm deep and same width as the windows, contribute to lower indoor temperatures during the summer, but cause a slight increase of the space heating demand (0.2 kWh/m^2), compared to if there were no fixed shading that would lower the effect of the free solar heat during the spring, autumn and winter months. This option was dismissed, due to difficulties in finding a good solution for fixing the shadings to the construction without causing additional thermal bridges and risk for moisture damage in the timber construction. However, vertical shadings, e.g., screens or venetian blinds, placed in the outmost air gap would be much more effective than a fixed horizontal shading [34]. A more detailed study on possible shading options was not performed within the project frame due to the policy of the Rental Housing Company in Växjö not to have any movable shading devices.

Figure 2. Annual peak load, space heating demand and maximum summer indoor temperatures with different window and shading options. No manual airing of the apartments was included in the simulations. By-pass of the heat exchanger was used in the simulation.

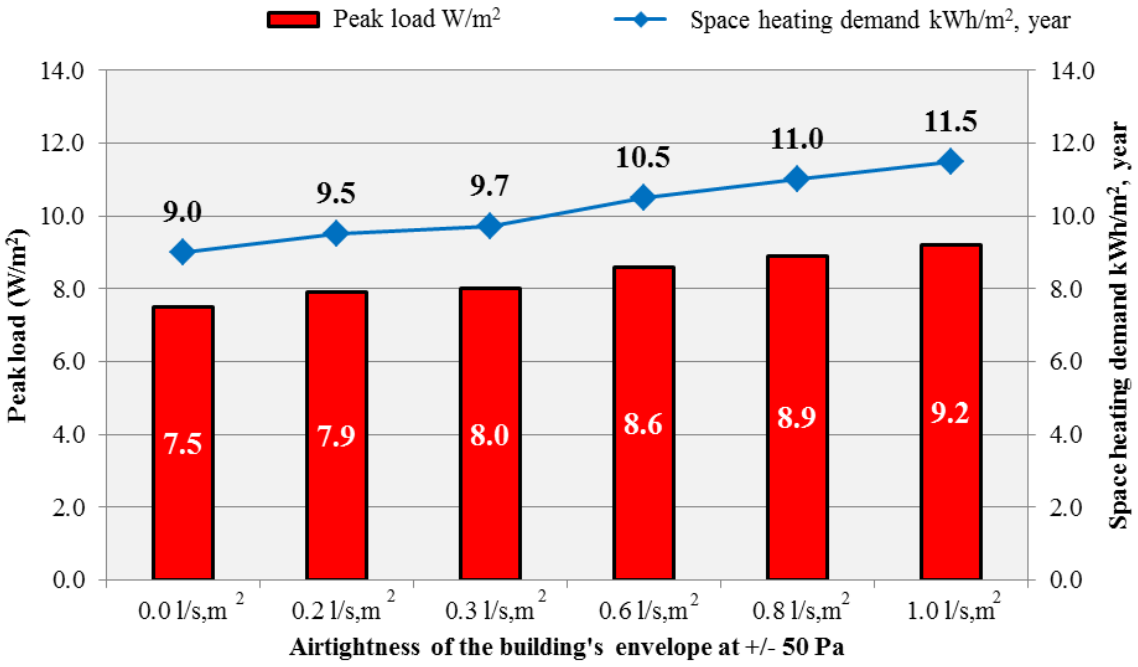


No airing options were simulated in this case, which contributes to the unrealistic situation, since occupants would have never allowed for such high temperatures to occur. Maximum simulated indoor temperatures during the winter months were in the range of 22–24 °C, while the minimum indoor temperature was set to 20 °C. The maximum daily average outdoor temperature used in the simulation was 27.7 °C. The option of using the by-pass of the heat exchanger in the DEROB-LTH simulation was chosen. A more detailed analysis of the summer indoor temperatures was done, where different manual airing options (windows closed, windows 25% open and 50% open) were analyzed for every

day between 17 h and 22 h during the period May 1 to September 30 [11]. Results showed no significant difference in indoor temperatures if the windows were 25% or 50% open. However, the simulations showed a risk of having two days with average daily indoor air temperatures above 26 °C. According to the Swedish National Board of Health and Welfare, maximum operative indoor temperature during summer months should be 26 °C, and only for short periods of time it is allowed to be 28 °C [35]. Having indoor air temperatures of 26 °C indicates a risk of getting operative temperatures at the same level or higher.

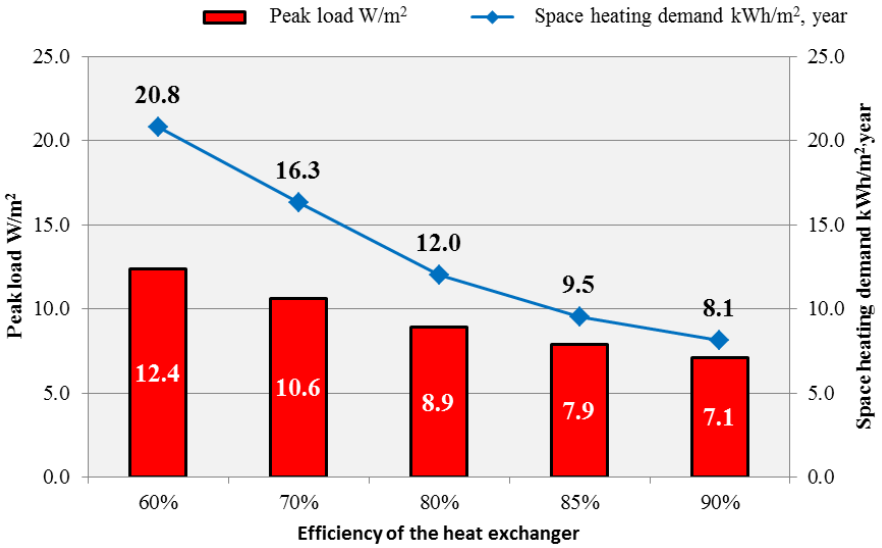
Changes in airtightness of the building's envelope have a large effect on the peak load and space heating demand (Figure 3). In case the airtightness is 1.0 L/(s m^2) at +/− 50 Pa, the peak load would rise by 1.3 W/m^2 (17%) and the space heating demand by almost 2 kWh/m^2 (20%), compared to the results achieved for the targeted 0.2 L/(s m^2). The measured airtightness of the building was, on average, 0.19 L/(s m^2) at +/− 50 Pa, which is below the defined level of 0.3 L/(s m^2) at +/− 50 Pa in the voluntary Swedish Passive House criteria. Swedish Building regulations do not require a specific airtightness for buildings.

Figure 3. Peak load and space heating demand for different airtightness of the building's envelope. The design target was 0.2 L/(s m²) at +/− 50 Pa, whereas the Swedish voluntary Passive House criteria specify the limit to be 0.3 L/(s m²) at +/− 50 Pa.



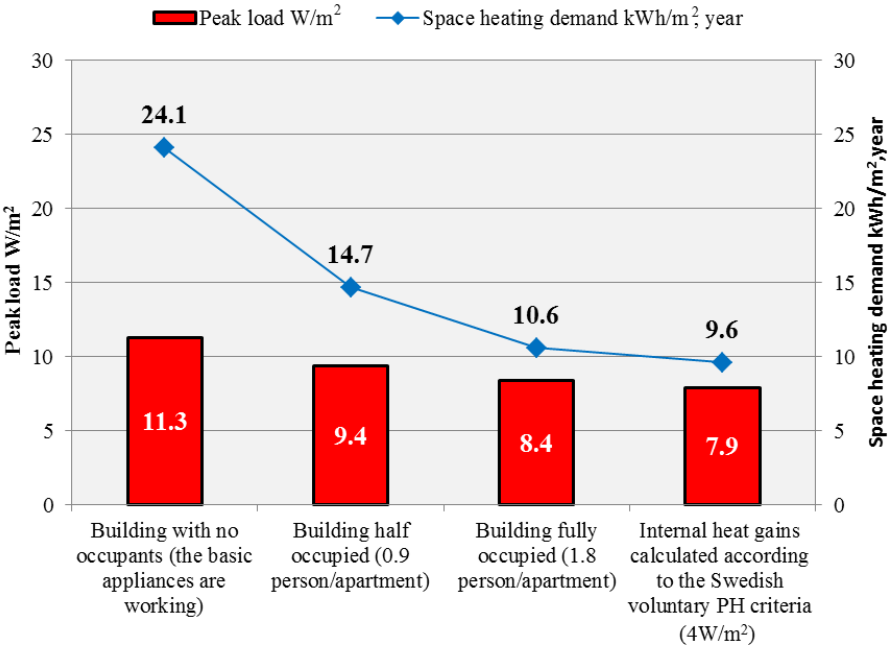
A 25% less efficiency of the air-to-air heat exchanger (from 85% to 60%) would result in a 4.5 W/m^2 (57%) higher peak load and a 11.3 kWh/m^2 (118%) higher space heating demand (Figure 4). The installed double plate heat exchanger was designed to have 85% temperature efficiency, while in the winter months, approx. 30% of the air flow passes through the by-pass valve, which in the case of −5°C outside temperature would result in approx. 52% temperature efficiency of the heat exchanger. In extremely low outdoor temperatures, the air flow through the by-pass might need to be higher, in order to prevent the icing of the heat exchanger. A lower efficiency of the heat exchanger results in higher peak load and space heating demand.

Figure 4. Peak load and space heating demand depending on the efficiencies of the heat exchanger.



Internal heat gains have a large effect on the space heating demand, as expected (Figure 5). The manually calculated internal available free heat gains of a fully occupied building (3.3 W/m^2 living area) fit quite well with the recommended maximum (of 4 W/m^2 living area) in the Swedish voluntary Passive House criteria. There is, however, a significant difference between the effect of internal heat gains when the building is half occupied (2.19 W/m^2 living area) and if the building is empty (0.77 W/m^2 living area).

Figure 5. The effect of different levels of internal heat gains on peak load and space heating demand.

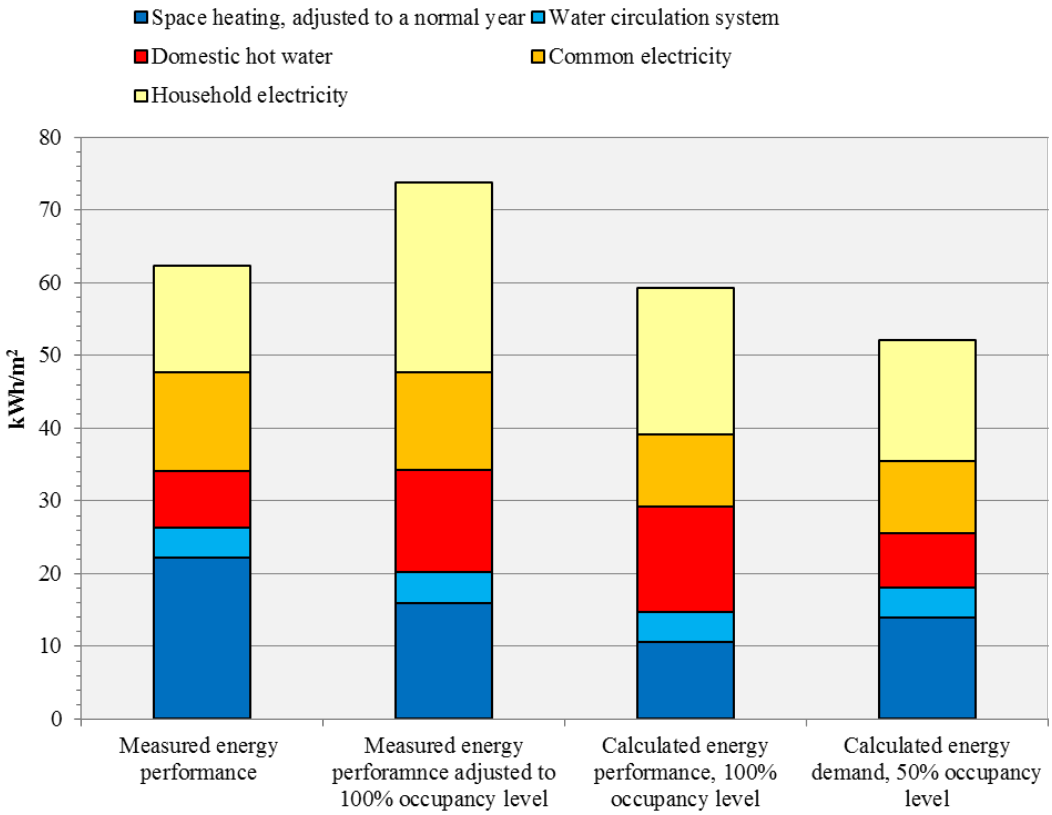


The monitored energy use was analyzed for the period of 1 January 2010 to 31 December 2010. The total delivered ("bought") energy during 2010, revised to a normal year, was 47.6 kWh/m^2, excluding

household electricity (Figure 6). During the analyzed period, the building was on average 55% occupied (18 rented apartments). Building occupancy level has an impact on the total energy use of the building. Space heating demand, DHW and household electricity were adjusted to 100% occupancy level. Space heating demand is affected by internal free heat from people, where the parameters in Table 5 were used for calculation. DHW use is affected by the number of people living in the building, where the average number of inhabitants (1.8) and their DHW use per apartment, calculated from the measured number of inhabitants per apartment during the analyzed period, was recalculated to fit the 100% occupied apartments. For the calculated values, the equation given in the voluntary Swedish Passive House criteria was used, where a person on average uses 18 m^3 of DHW per year [5]. For converting the volume of DHW into energy use, Equation 1 was used [5].

$$[Q_{DHW} = 1.16 \text{ kWh/°C} * 47\text{°C} * X \text{ m}^3{}_{DHW} \text{ [kWh]}] \quad (1)$$

Figure 6. Total energy use. Monitored values are adjusted to 100% occupancy level and compared to simulated values for full and half occupancy. Space heating demand is adjusted to a normal year.



Household electricity use was also adjusted using the template for calculating household electricity use provided in the voluntary Swedish Passive House criteria (Equation 2) [5].

$$[\text{Total El} = 1040 \text{ kWh/(year, household)} + 300 \text{ kWh/(year, person)}] \quad (2)$$

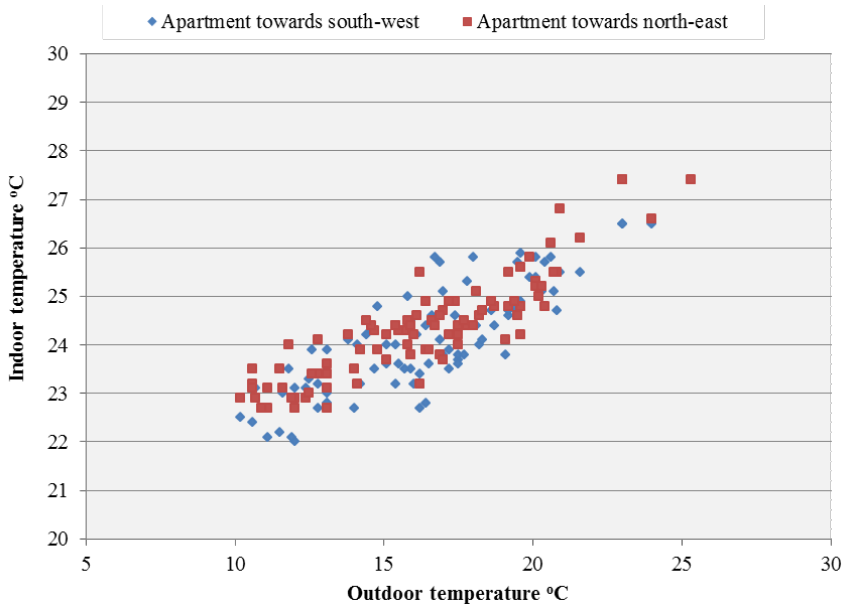
In the revision of the measured energy use to 100% occupancy levels, energy use for common electricity was not adjusted to the full occupancy level, since it is difficult to predict the electricity use of the elevator, due to higher occupancy rate.

Adjusted to the 100% occupancy level (for space heating demand, DHW and household electricity use), the building's total delivered energy would be 47.8 kWh/m^2. This corresponds to 61.3 kWh/m^2 of weighed energy, according to the energy factors for different energy sources given in the Swedish Passive House criteria. The adjusted measured space heating demand is 5.4 kWh/m^2 (51%) higher, while household electricity use is 6 kWh/m^2 (30%) higher than the calculated values for a fully occupied building.

The total amount of energy recovered from the waste water heat exchanger during the analyzed year was 0.62 kWh/m^2, which is only 2.4% of the amount of DHW used. Due to low occupancy levels, the efficiency of the waste water heat exchanger could not be fully evaluated. The efficiency of the heat exchanger is dependent on the occupancy levels and occupant behavior, but also on the installation and location of the device. The producer recommends installation close to the source and within the building envelope, to achieve maximum heat reuse capacity. The installed heat exchanger is used for recovering heat from two buildings, placed in the ground between them.

During the period 1 June–31 August 2010 the daily average indoor air temperatures were quite steady (22°C–27.4°C) compared to the daily average outdoor air temperature fluctuations (10 °C–25.3 °C). Two apartments at the topmost floor were analyzed in more detail (one towards SW and one towards NE), where the highest average daily indoor air temperature of 27.4 °C stayed for three consecutive days in the NE apartment, 11–13 July 2010, while in the SW apartment, the same temperature was recorded for only one day, 11 July 2010. Figure 7 shows the relationship between the indoor and outdoor air temperature during the analyzed summer period. Both apartments were used during the analyzed period (water and electricity use was recorded), which suggests that window airing was used for lowering the indoor temperatures in the SW apartment.

Figure 7. Measured indoor temperatures in two apartments at the last floor in relation to the outdoor temperatures.



During the period 1 January–31 December monthly average indoor temperatures were measured for six apartments on different floors and orientations. The monthly average indoor temperature was in the

range of 19.3 °C to 25.9 °C, whereas monthly average outdoor temperatures were in the range of −7.4 °C to 18.8 °C

During the first year in operation, many challenges with the installed systems were experienced: heating distribution to the top floors was insufficient; the control system for the by-pass in the air-to-air heat exchanger was adjusted several times during the winter season; the power of the central and individual batteries were adjusted several times; and the shunt unit at the central heating battery proved to be under-dimensioned.

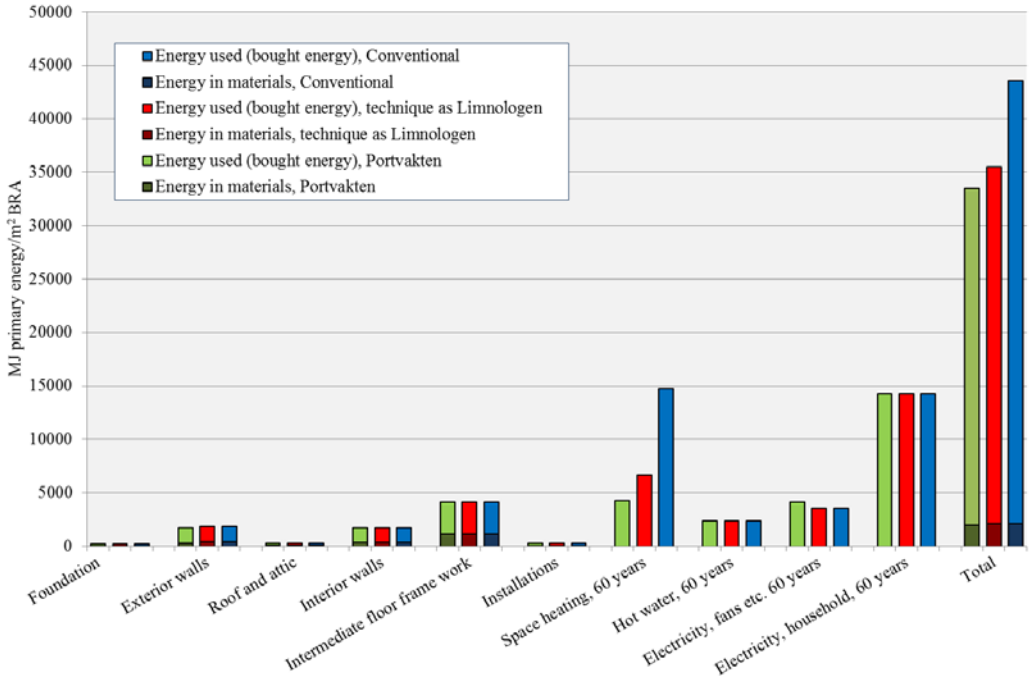
4.2. Occupant Behavior

A questionnaire was sent out to the inhabitants of the two Southern Portvakten buildings after one year of occupancy. In total, 19 responses were received out of 39 that were sent out. The main conclusions from the questionnaire include that 14 out of 19 manually ventilated the apartment, by opening a window or the balcony door, on a daily basis during the heating season. Also, the possibilities for individual control of the indoor air quality by adjusting the ventilation system were considered to be rather poor, very poor or with no possibility, by 12 out of 17 responses. Own kitchen smells bother 14 out of 19 responses, although there is a possibility for forced ventilation above the stove. On average, the air quality in the apartments was considered as rather good to very good, where no one experienced the air quality to be very bad in any of the rooms, except one inhabitant that thought the air quality in the bathroom was very bad. Furthermore, condensation on the outside of the window glass often bothers nine inhabitants and sometimes bothers six inhabitants out of 18 that have replied to that question.

4.3. Environmental Analysis

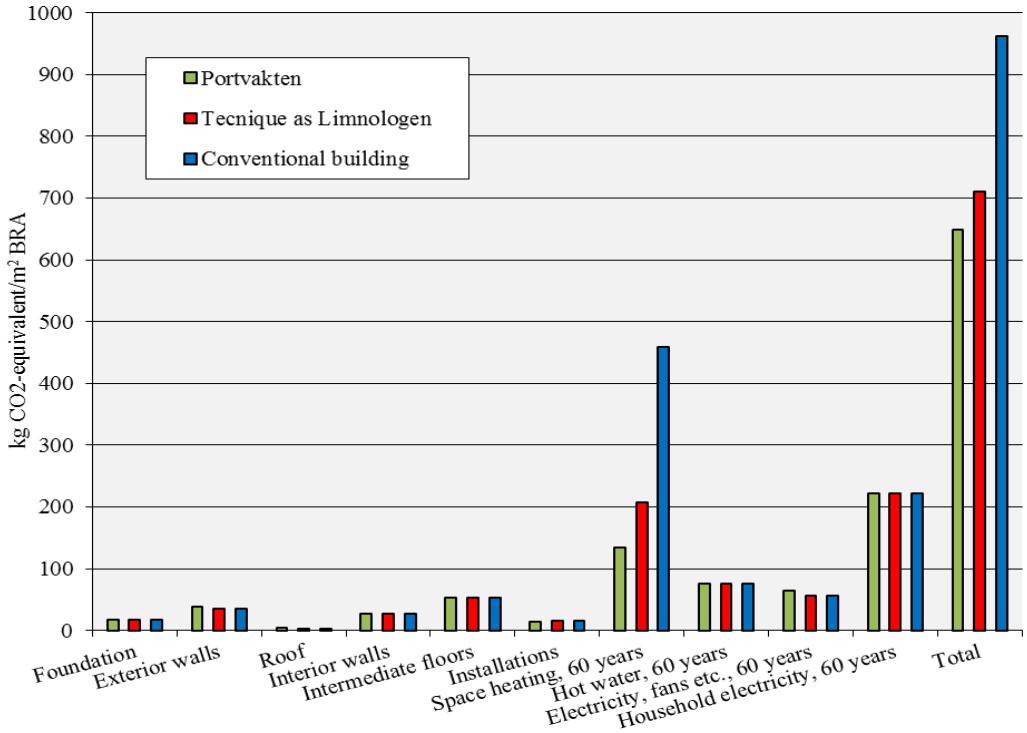
The Life Cycle Assessment (LCA) shows that the focus changes from the need to further lower the energy use for heating to other energy related aspects. The overall primary energy use of the Portvakten building during 60 years of operation was analyzed and compared with if it was built as a reference (Limnologen) or a conventional building. The construction of the three buildings is assumed to be the same (timber frame construction), adjusted for the thermal performance of the building envelope needed to satisfy their respective energy demand. The main difference in the installations of the three buildings is for space heating, where, in the Portvakten building, an air-to-air heat exchanger with 85% efficiency rate was used, in Limnologen, an air-to-air heat exchanger with 83% efficiency rate was used, and in the conventional building space, heating is provided using radiators connected to the district heating system, with an extract air ventilation system. In low energy buildings, the single biggest environmental impact comes from household electricity use. A fraction of the additional energy used to produce building elements for low energy buildings, compared to contemporary buildings, in combination with higher electricity use for fans and pumps (conventional buildings often use less energy for fans and pumps, if any), result in significant primary energy savings related to the significantly reduced energy used for heating. In a conventional building, built according to the Swedish building norms, the material extraction and production is in relative terms not important in the same way, due to the high energy use for heating; see Figure 8. All compared buildings are supplied with heating and hot water from the district heating system.

Figure 8. Use of primary energy, including 60 years of operation MJ/m^2.



When analyzing the GWP, the tendency is the same as for primary energy. The increased environmental impact for the extra material needed to achieve an energy-efficient building is negligible; see Figure 9. At Portvakten, the materials used for the heating installations have less impact, since there is no need for radiators or floor heating installations, as compared to if technologies, as in Limnologen or the conventional building, where used.

Figure 9. Potential contribution to global climate change, including 60 years of operation, kg CO_2-eq/m^2.



5. Discussion and Conclusions

The building's measured energy use for space heating (22.2 kWh/m^2, normalized values) is higher than the calculated values (10.6 kWh/m^2, normalized values), which can be explained by low occupancy levels, higher indoor temperatures (19.3 °C to 25.9 °C) than the ones used in the calculations (20.0 °C), manual ventilation of the apartments by the occupants during the winter period, as well as technical system adjustments during the monitoring period. Still, the weighed energy performance of 61.3 kWh/m^2 was only 1.3 kWh/m^2 higher than the recommendations for passive houses in the Swedish voluntary Passive House criteria [5]. Previous experiences with measured energy performance of other passive house projects in Sweden showed higher energy use compared to the calculated values [21,32,36]. The differences were also noted in the first passive houses built in Germany [3,37]. However, measured energy use for heating was significantly lower than the Swedish national code at the time of construction, 110 kWh/m^2 [10], and revised, 90 kWh/m^2 [38], and of the existing multifamily housing stock, 125–165 kWh/m^2 [36].

Parametric studies showed that the choice and functioning of the building elements and technical solutions can have a significant impact on the energy performance. Solar control glass showed to be the best available shading option for the research object. This was at the cost of higher peak load and space heating demand, but also has consequences on possibly higher electricity use for lighting during the cloudy and winter periods. Building's envelope airtightness has a significant impact on the energy performance, which can also indicate that user behavior and long-term manual airing of the apartments, even as a small window opening, can have a significant effect on the heating energy use. Heat exchanger efficiencies are significantly affected by infiltration and exfiltration, especially during the winter months [39], indoor and outdoor temperatures, air humidity, airtightness of the building envelope and by-pass options (for minimizing the risk of freezing of the heat exchanger). A 25 percentage units less efficiency of the heat exchanger can result in over a doubled space heating demand. Energy simulations show that the influence of a half occupied building compared to no occupants has greater effect on the building's energy performance (14.7 kWh/m^2 compared to 25.1 kWh/m^2) than of a fully occupied building compared to half occupancy (10.6 kWh/m^2 compared to 14.7 kWh/m^2). This is due to internal free heat from household appliances and DHW circulation losses, which occur even if only a few people live in the building. The assessment of available internal heat gains in the analyzed building (fully occupied) for the calculation of the peak load, showed to be in line with the recommended values in the voluntary Swedish Passive House criteria, 4W/m^2. Due to the fast development of technical building systems and household appliances, internal heat gains might change for residential buildings in the future. In addition to internal heat gains, solar gains should be taken into account when simulating the space heating demand and indoor temperatures.

Low energy buildings have a significant impact on lowering the primary energy use and global warming potential, primarily during the operation period through lowering energy need for heating. The results showed a clear need for moving the focus from minimizing the heating demand to household electricity, which requires action both in developing energy-efficient and smart appliances, and changing user behavior. The study did not include a comparison in primary energy use and GHG emissions if other construction materials were used, like concrete or steel, where previous studies have shown a significant advantage of using timber frames in favor of concrete frames [40].

Measured daily average indoor air temperatures (1 May–30 September) were quite even in the analyzed apartments, regardless of the orientation or floor. Measurements registered a three day consecutive occurrence of average indoor temperatures above 26 °C in one of the analyzed apartments, which fit quite well with the simulation of manual airing with 25% windows open. Still, the summer of 2010 was somewhat colder (in May and August) compared to a normal year.

Occupants might have a big influence on the building's energy performance and functioning of the ventilation and heat exchange system. This is especially true during the winter, when most of those that responded to the questionnaire regularly manually ventilate the apartment, even when the indoor temperature is, by some, experienced as low. Higher space heating need can be explained by the energy loss created by regular window airing of the apartments by the majority of the inhabitants that responded to the questionnaire. The air quality in the apartments should be analyzed to confirm the experiences of the inhabitants with own kitchen smells that might be the cause to often use window airing.

Experiences from this project show that the first year in operation is not the ideal year for drawing conclusions if the constructed building meets the design targets, especially if the building systems and solutions are unique. Fully functioning technical systems, as well as high occupancy level, is crucial for energy performance analysis, since it is assumed that during most of the building's lifetime, those two aspects would be met.

To conclude, it is possible to construct and build low energy multifamily buildings in prefabricated timber elements. Several aspects may contribute to better energy performance of the Southern Portvakten building: optimal mechanical system adjustments, full occupancy, improved user behavior with reduced window airing during the winter months, as well as use of low energy lighting and household appliances. None of these measures require large interventions or financial investments.

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