NEW CONCEPT OF A PASSIVE HOUSE – FROM DESIGN TO REALISATION

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ABSTRACT

The article describes details of a new concept of the passive house. The passive house is a synonym for energy efficient house with energy demand for heating Q_H less than 15 kWh/m2·a and a primary energy demand Q_{PE} less than 120 kWh/m2·a. In climates where active cooling is needed, the space cooling energy demand Q_C roughly matches the heat demand requirements above, with a slight additional allowance for dehumidification. Another requirement is related to air-tightness. Uncontrolled air leakage shall be less than 0,6 of heated volume per hour at increased and decreased pressure of 50 Pa. Thermal comfort must be met for all living areas during winter as well as in summer, with not more than 10 % of the hours in a given year over 25 °C.

This concept at the beginning encountered energy efficiency only but had a few drawbacks in terms of user comfort and potentially even health aspects. Two main drawbacks were dry air in winter and unknown air quality in terms of CO_2 which could resulted in bad air quality in spite of the mechanical ventilation system with heat recovery (MVHR). At the passive house conference in 2008 (Nürnberg, Germany) I presented my own passive house project, which introduced floor heating only instead of heating through the ventilation system [1]. Another improvement was implementation of the MVHR with rotary air-to-air enthalpy wheel which was developed many years ago but commercially available device with sufficient efficiency was offered shortly before my project started. This system prevented fast dehumidification of indoor air in winter. Based on the developed CO_2 measurement unit in our laboratory the speed of ventilation in the heat recovery system was regulated in order to maintain fresh air under the limit 1000 ppm of CO_2.

After almost 4 years of living in the house and regular measurements of climate variables (temperature, relative humidity, CO_2), analysis of energy invoices for 4 winter seasons (2011-2014) with calculated energy consumption proved the economic investment and energy efficiency with increased living comfort and assured healthy environment in terms of fresh air.

INTRODUCTION

People are more and more aware that energy efficiency in every respect is not only necessary from the economic point of view but is also necessary to preserve our environment and enables sustainable living. In the EU 40 % of energy is used for heating of buildings. The EU has set 20 % targets for renewable energy, greenhouse gas reduction, and energy efficiency until 2020 compared to 1990 levels. The EU has set itself a long-term goal of reducing greenhouse gas emissions by 80 % to 95 % when compared to 1990 levels by 2050. To achieve these goals, significant investments need to be made in new low-carbon technologies, renewable energy, energy efficiency and grid infrastructure [2].

In this respect it is important to stimulate construction of energy efficient buildings where payback period is relatively short. Taking into account that construction of a building is a lifetime investment the payback period of less than 10 years could be considered as short and as such would stimulate people for investments. This example will be used to prove the possibility and compatibility of economical construction of energy efficient buildings and buildings in which comfort of living and healthy environment is provided.

NOMENCLATURE

CO_2	[ppm]	carbon dioxide, greenhouse gas
COP	[-]	coefficient of performance
Q	[kWh/m^2·a]	normalized energy consumption per m^2 and year
q50	[m^3/h·m^2]	standard for measuring the air tightness
MV	[-]	mechanical ventilation
MVHR	[-]	mechanical ventilation with heat recovery
U	[W/m^2·K]	overall heat transfer coefficient
ACH50	V/h	air changes per hour at pressure 50 Pa
ACHn	V/h	natural air changes per hour

Special characters

ppm	[-]	part per million
r.h.	[%]	relative humidity
g-value	[-]	solar energy transmittance of glass

Subscripts

H	heating
PE	primary energy
C	cooling
L	losses
G	gains
T	transmission losses
V	ventilation losses
I	internal heat gains
S	available solar heat gains
w	window

DESIGN, CALCULATION AND CONSTRUCTION

Before construction of an energy efficient building it is important to verify the design with appropriate calculations. Calculation of numerous parameters for a passive building is possible with the Passive House Planning Package (PHPP), developed by the Passive House Institute, Darmstadt, Germany. It is the key design tool used when planning a passive house and as such, serves as the basis of verification for the passive house standard. A passive house is far more than the sum of its elements. Precise planning is required in order to ensure that the components used work together to achieve the desired result. Based on the large part on European norms, the PHPP makes use of numerous tested and approved calculations to yield a building's the heating, cooling and primary energy demand, as well as its tendency to overheat in the warmer months. While the PHPP was developed specifically for Passive Houses, it is a design tool that may also be used for other buildings, including retrofits of historical buildings [3].

The annual heat demand Q_H is the difference between heat losses Q_L and heat gains Q_G:

$$Q_H = Q_L - Q_G \tag{1}$$

where heat losses consists of transmission heat losses Q_T and ventilation heat losses Q_V:

$$Q_L = Q_T + Q_V \tag{2}$$

while heat gains consists of internal heat gains Q_I and available solar heat gains Q_S:

$$Q_G = Q_I + Q_S \tag{3}$$

In the house with efficient and extensive insulation the largest part of energy is needed for the ventilation of air and the regulation of temperature and humidity in the supply air. By the integration of a heat exchanger a huge improvement in terms of energy efficiency was possible. This efficiency was further improved by the use of enthalpy exchangers [4]. In contrast to common heat exchangers an additional exchange of humidity between supply and exhaust air is possible. However, rotation exchangers have hygienic deficiencies. If supply and exhaust air are directly contacted a re-circulation of germs, bacteria and other pollutants cannot be ruled out. Therefore such technical applications in hospitals and clean rooms are out of the question.

For example, in the ambition to produce a more energy efficient housing stock, the Scottish Building Regulations have tightened the requirements for the air tightness of new buildings [5]. The measurement standard is called 'q50′, which measures the escaped air [in cubic meters] per hour in relation to the surface envelope area of the building [in square meters], when the house is set under pressure of 50 Pascal. All controlled ventilation openings are excluded from the test. The smaller the value, the more sealed the building, Figure 1. If the test result exceeds 7 $m^3/(h{\cdot}m^2)$ at 50 Pa, it has failed and remedial measures need to be taken. However, if the building is tighter than 3,5 $m^3/(h{\cdot}m^2)$ at 50 Pa, mechanical ventilation (MV) – and in particular mechanical ventilation with heat recovery (MVHR) – is a requirement.

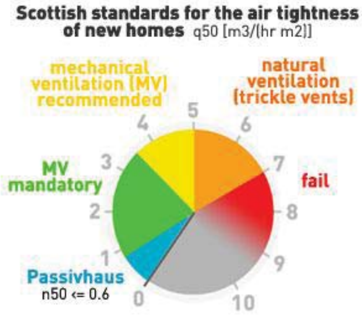

Figure 1 Air tightness requirements

As the expert for temperature and humidity I had several concerns about the concept of the passive house at the time when I was constructing my own house. The first concern was the mechanical ventilation system, which in the old concept of passive house provided also heating by warming the air in the ventilation system with the heat pump. The problem in winter is that outside fresh air contains low absolute humidity (e.g. at 0 °C and 90 % r.h. absolute humidity of air is 4,4 g/m^3 which decreases with lower temperature. When such air comes into inner space with room temperature of 20 °C it has a low relative humidity of 25 % r.h. [6], which is far from the comfort range of 40 % r.h. to 60 % r.h. at the room temperature. Therefore I proposed the new concept of passive house in which heating was calculated, designed and realized through the floor heating only, with low temperature regime (maximum temperature of inlet water 35 °C), [1]. The ventilation system in this case did not require additional heating. It was realized with the heat recovery unit with rotary air-to-air enthalpy wheel, which enables up to 70 % recovery of humidity inside the thermal envelope.

Inlet air was additionally conditioned with the defroster unit to increase the heat exchange efficiency from 80 % to 92 %. Possibility was also to use the subsoil heat exchanger but that would require at least 50 meters of special tubes (antistatic, antibacterial). Drawbacks at approximately the same level of investment are an open system, where insects at least would be a problem, condensation problem in the tubes, and limited duration of antibacterial protection.

The heating and hot water supply was provided by the bivalent heat pump unit with ground source heat collector based on 6x100 meters of pipes, which were placed in loops with 30 % overlapping at the depth of 1,5 meter in a wet soil (conservative energy collection rate 25 W/m), Figure 2.

Orientation towards south (7 ° deviation) and 50 m^2 (73 % of window area) of triple glazed windows (U_w=0,74 $W/m^2{\cdot}K$, g=0,52) on the south facade generate around 45 % of energy for heating. Shading in summer and other seasons is provided with blinds, which are actively regulated based on internal temperature and solar availability. Master function in regulation of blinds has the wind speed sensor to protect damage of blinds, if the wind is stronger than 60 km/h.

Figure 2 Ground source heat collector

Although architecture was designed as dismembered, as shown in Figure 3 and Figure 4, construction with almost negligible or well dampened thermal bridges and some additional insulation enabled achievement of the passive house standard. The garage and cellar were built with the same construction material Isorast® [6] but outside the thermal envelope and therefore less insulation was used. The list of U values is given in Table 1.

Table 1 List of U values for assembly elements

Assembly No.	Assembly Description	Total Thickness	U-Value
		m	$W/(m^2K)$
1	ground floor slab	0,850	0,10
2	exterior wall ambient Isorast superdickwandstein 43,75 cm	0,478	0,11
3	exterior wall ground Isorast dickwandstein 37,5 cm	0,455	0,11
4	inclined roof	0,483	0,09
5	flat roof (connection)	0,563	0,11
6	ceiling (down to garage)	0,563	0,11
7	floor slab unheated basement	0,740	0,45
8	exterior wall ambient Isorast dickwandstein 37,5 cm	0,415	0,14
9	exterior wall ground Isorast wandstein 31,25 cm	0,393	0,14
10	exterior wall ambient Isorast wandstein 31,25 cm	0,333	0,19
11	Knauf partition wall bedroom-bathroom	0,125	0,35
12	cassette for blinds as thermal bridge	0,265	0,29

The design calculation was based on homogeneous temperature of 20 °C inside the thermal envelope with treated floor area of 241 m^2 and volume of 626 m^3. The construction in practice took into account different temperatures inside the building in order to increase living comfort. Toilets and bathrooms have higher temperature (23 °C to 24 °C), while sleeping rooms have lower temperature (18 °C to 19 °C). Regulation of different temperature with floor heating is rather trivial but important is also to limit the heat transfer between neighboring rooms with different temperatures. In this respect warmer and colder rooms shall be separated with optimum insulation to prevent increased heat transfer. This was achieved by placing 5 cm of rock wool inside the lightweight walls which at the same time serves as the noise attenuator.

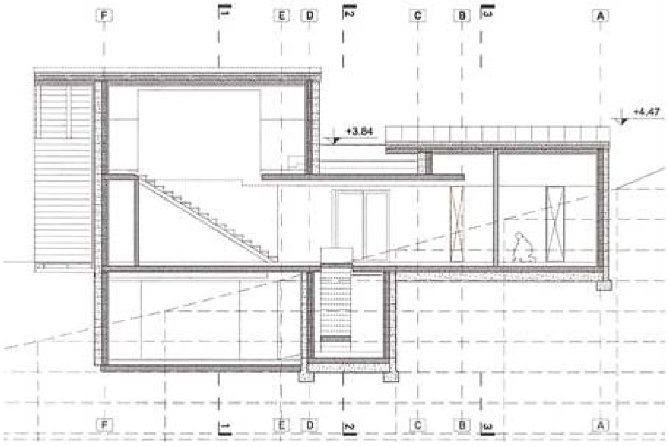

Figure 3 East view cross section

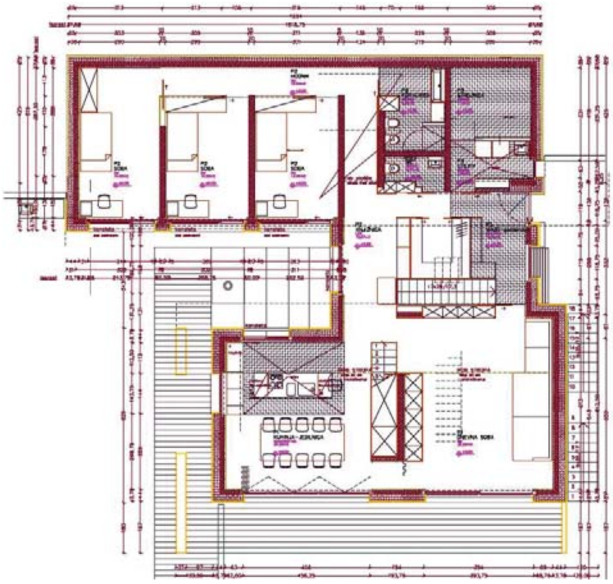

Figure 4 Ground floor

MEASUREMENTS AND VERIFICATION

Since moving into the house in July 2011 regular measurements were performed with 15 calibrated data loggers for temperature and 6 data loggers for humidity with data acquisition interval of 15 minutes. Later we developed also a logger for CO_2, which was moved around the house and had data acquisition interval 10 seconds. The main purpose of measurements was monitoring of ambient conditions in terms of comfort and healthy environment.

Temperature

Measurements of temperature showed very comfort temperature distribution with lower temperatures in bedrooms and higher temperatures in bathrooms and toilets. In year 2013 average monthly temperatures varied mainly between 19 °C and 23 °C except in summer peak of July, where temperature in the loft was around 24 °C (Figure 5). The most important is that overheating above 25 °C did not occur in spite of warmer years than the average climate data, which was taken into account in the design phase (Table 2). Obviously average monthly temperatures in 2013 were higher than 10 year average (1998-2007) used in calculation during the design phase. Average monthly temperatures during the heating season in 2014 were record high since temperature measurements are implemented (Figure 6).

Table 2 Average temperatures in 2013, 2014 and climate data for calculation respectively (values in °C)

Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec
2,1	1,3	4,8	12,8	15,3	20,4	24,2	23,4	17,8	14,3	7,9	3,1
6,6	5,7	11,1	14,1	16,5	20,7	21,5	20,7	17,4	14,8	10,1	5,5
0,7	2,4	7,0	11,1	16,5	20,4	21,9	20,6	15,5	11,8	6,6	1,3

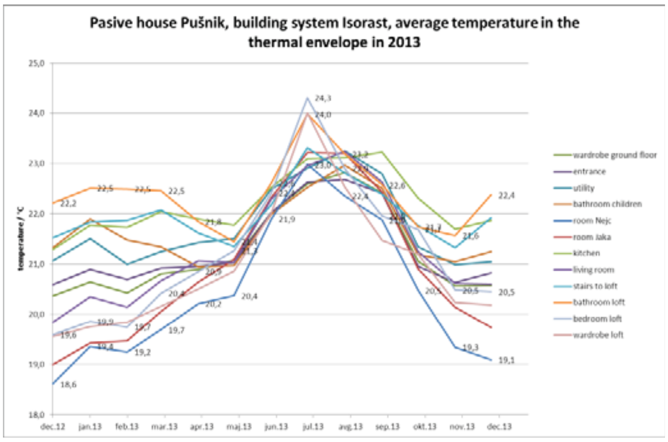

Figure 5 Average monthly temperature in 2013

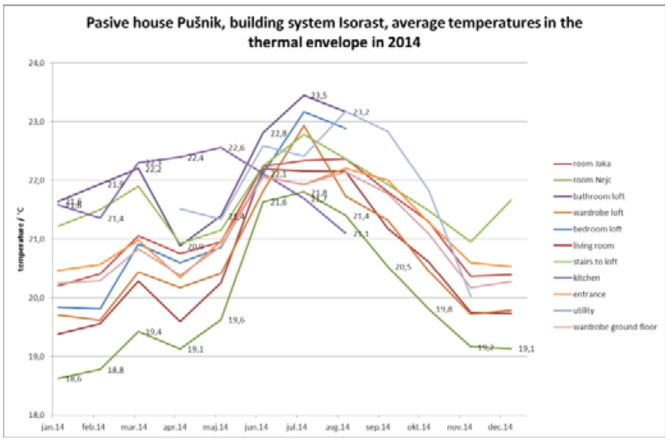

Figure 6 Average monthly temperature in 2014

Relative humidity

Measurements of relative humidity showed that most of the year the relative humidity is in the comfort zone between 40 % r.h. and 60 % r.h. That is the most important in winter. In year 2013 was a lot of precipitation therefore summer and winter months were slightly above the comfort zone but still below 70 % r.h. (Figure 7).

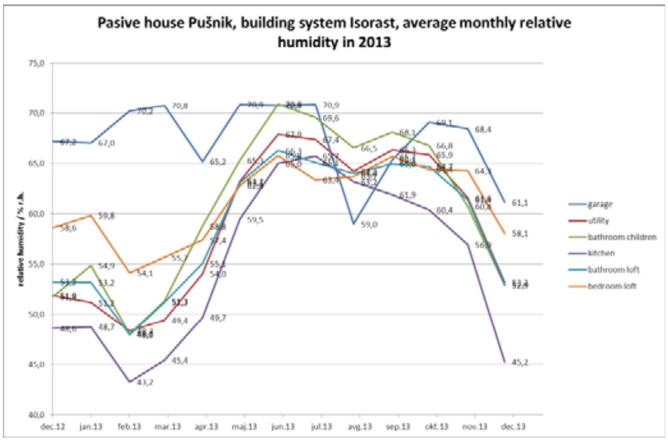

Figure 7 Average monthly relative humidity in 2013

Even more precipitation were in the first half of 2014 but indoor relative humidity was not much different to previous year (Figure 8) due to effective ventilation system and natural materials which serve as excellent humidity absorbers (wooden floor and furniture, lime-gypsum plaster).

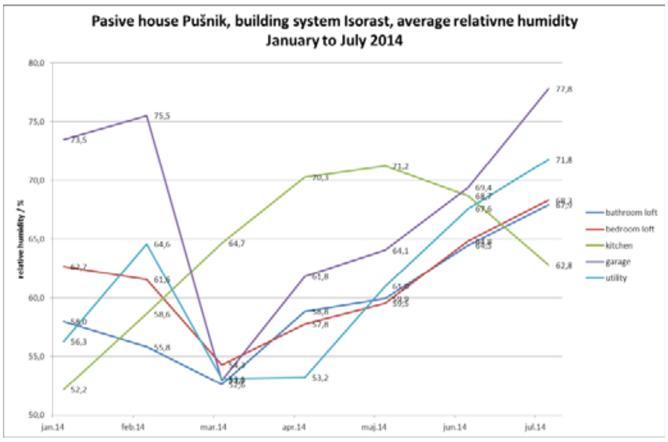

Figure 8 Average monthly relative humidity in the first half of 2014

Carbon dioxide

Carbon dioxide (CO_2) is a colorless and odorless gas that exists in the earth's atmosphere and which is dangerous in high concentrations. The proportion of CO_2 in natural ambient air is about 0.04 % or 400 ppm. When humans and animals exhale this gas, it is quickly mixed with the ambient air, including in rooms that are well ventilated.

A high CO_2 content becomes apparent in humans through rapid fatigue and loss of concentration. The negative effects become noticeable more quickly in small rooms in which there are many people (e.g. conference rooms).

In order to initiate suitable countermeasures such as an increase in the supply of fresh air, it is important in modern climate control systems to measure not only parameters such as relative humidity and temperature, but also the CO_2 content. The concentration of CO_2 is regarded as an important indicator for the quality of room air.

The effects of increased CO_2 levels on adults at good health can be summarized [8]:

- normal outdoor level: 350 - 450 ppm
- acceptable levels: < 600 ppm
- complaints of stiffness and odors: 600 - 1000 ppm
- general drowsiness: 1000 - 2500 ppm
- adverse health effects expected: 2500 - 5000 ppm
- maximum allowed concentration within an 8 hour working period: 5000 ppm

Measurements of CO_2 showed how its level depends on the speed of fans, persons present and their physical activity. MVHR system maximum capacity of exchange is 370 m^3/h. At the fan speed 1 30 % of the maximum capacity is exchanged, which is 110 m^3/h, at the fan speed 2 50 % of the maximum capacity is exchanged, which is 185 m^3/h, at the fan speed 3 80 % of the maximum capacity is exchanged, which is 300 m^3/h and that is almost half of the house volume. This means that at the maximum fan speed 3 the complete air in the volume is changed in some more than 2 hours. It is important to emphasize that measuring system of CO_2 was not calibrated because there are very few laboratories which could calibrate CO_2 meters. Nevertheless, relative changes are still obvious while absolute values in the open air are comparable to 350 ppm. There is almost no difference in the CO_2 level, if one or two persons are sleeping in the bedroom, which proves effectiveness of the ventilation system at the fan speed 2 or more, Figure 10. If the graph resolution is enhanced it is obvious that presence of another person increases CO_2 level for approximately 300 to 400 ppm at the fan speed 1, for approximately 200 ppm at the fan speed 2 and for approximately 100 ppm at the fan speed 3. It is obvious that when the door to terrace is open the CO_2 level drops quickly to 400 ppm or less. The same level is reached also a few hours after a room is not occupied with persons. Under normal conditions the fan speed 1 is not enough to provide CO_2 level below 1000 ppm, Figure 11. Capacity of air supply to the rooms depends on their volume and expected occupancy. Capacity of supply (bedrooms, living room, library) and exhaust air (toilets, bathrooms, kitchen, utility, wardrobe) are completely balanced. Bedrooms supply capacity is 50 m^3/h, living room supply capacity is 125 m^3/h.

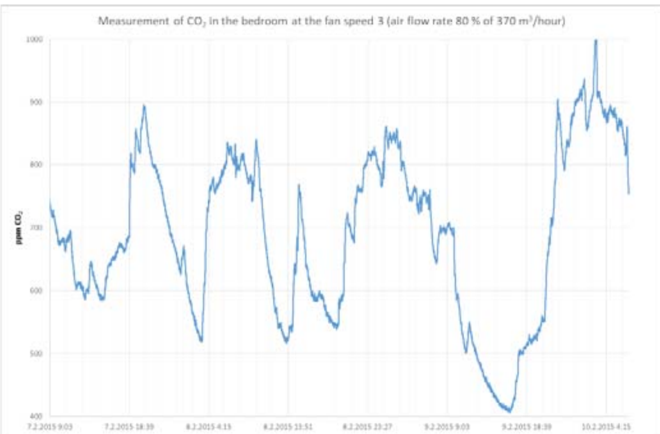

Figure 9 CO_2 level at the fan speed 3

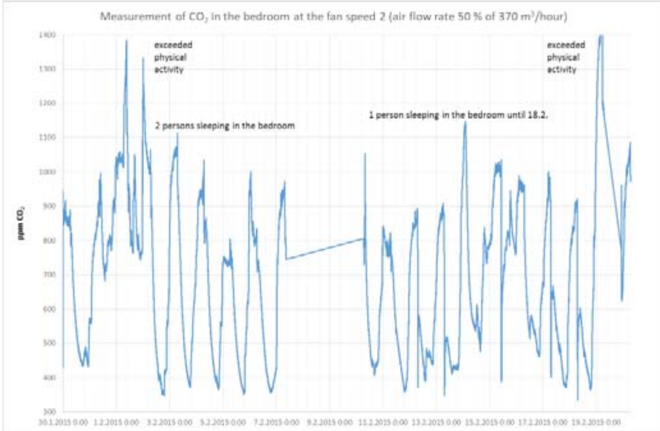

Figure 10 CO_2 level at the fan speed 2

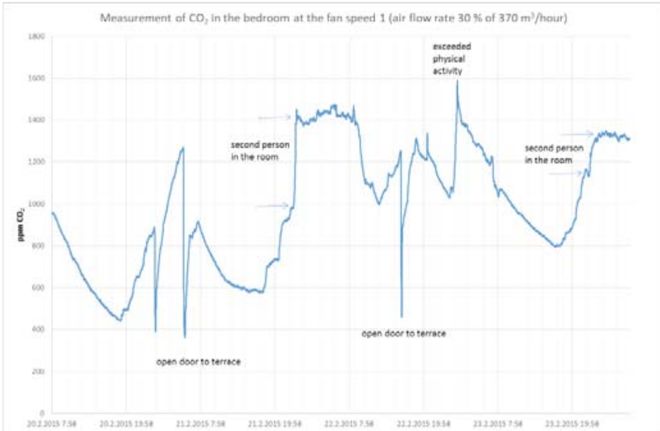

Figure 11 CO_2 level at the fan speed 1

Blower door test and thermal imaging

The effectiveness of the MVHR depends on air tightness of the building. This was measured with door blower test [9]. In addition to quantifying air sealing effectiveness, a blower door test can also help find defects, especially in conjunction with an infrared thermal imaging camera. The blower door will exacerbate the natural infiltration occurring in a house making air leaks easier to find because the air outside forcing its way in shows up as a different colour on the IR camera, Figure 12. To measure the amount of leakage we performed a blower door test, which was comprised of a calibrated fan, a mounting system to attach the fan to an exterior door, and a manometer to measure the amount of air needed to keep a house at an elevated pressure of 50 Pascal. For example, a code-built new home with decent air sealing might have 7 air changes per hour at 50 Pascal (ACH50), meaning if we kept the blower door running for an hour it would pump in enough air to completely replace the home's air 7 times. This would translate to about 0.35 natural air changes per hour (ACHn), or about one complete air replacement every 3 hours.

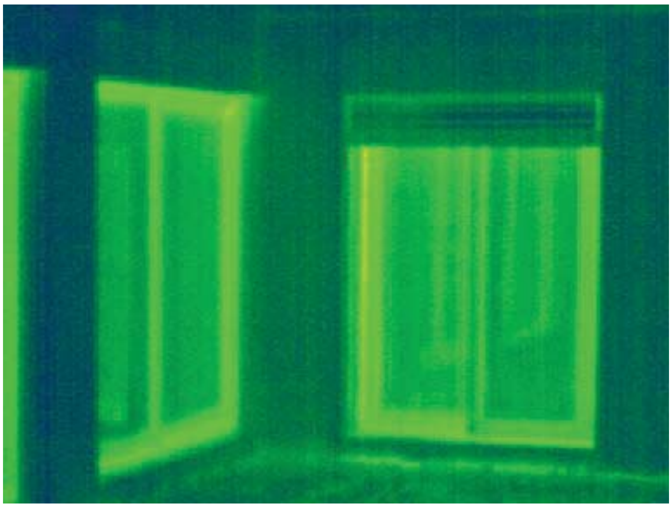

Figure 12 thermal imaging of building elements

Thermal imaging of entrance door revealed poor sealing which required adjustment of door fittings, Figure 13.

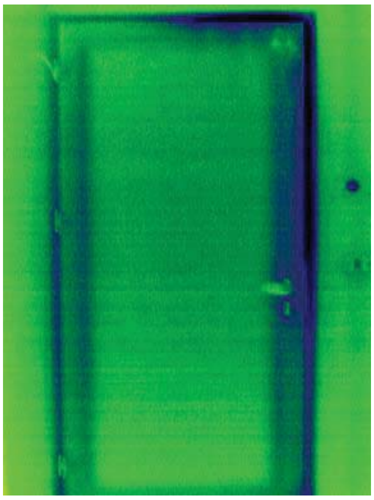

Figure 13 thermal imaging of entrance door

Final verification

The final verification of the passive house standard was based on analysis of invoices for electricity, which is the only energy source. For 4 winter seasons the average cost of electricity was 193 EUR, with average heating demand 8 kWh/m2·a and the average total energy consumption in 3 years of 32 kWh/m2·a. Obviously the passive standard was achieved in spite of higher temperatures in the last few years.

CONCLUSION

The two year design phase of the new passive house concept was successfully realized after less than two year construction phase. Accurate and thorough design required at least the same level of accuracy, consistency and thoroughness in construction to achieve the required objectives. The results of verification measurements and analysis of energy invoices for three and a half year showed that the passive house standard was easily achieved in spite of dismembered architecture. Helpful were higher temperatures than those used in the climate data of PHPP for calculation of energy balance. Energy efficiency exceeded design calculations, which were performed very conservatively in terms of temperatures, heat pump coefficient of performance (COP) due to heat exchange rate of heat pump ground source heat collector, efficiency of heat recovery system with enthalpy wheel.

From the economic point of view it is important to emphasize that 8 % higher investment in better insulation, better windows, automated blinds, ventilation system with defroster for preconditioning of supply air, heat recovery system with rotary air-to-air enthalpy wheel, floor heating, bivalent heat pump with ground source heat collector, (47.000 EUR), compared to minimum allowable construction standard in Slovenia with heating demand up to 75 kWh/m2·a, (17.000 EUR) resulted in the energy efficient passive house with healthy and very comfortable indoor environment, where payback period on investment is less than 10 years.

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