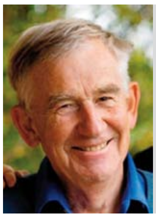
Energy-Efficient Passive House using thermal mass to achieve high thermal comfort



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Introduction

A five-storey apartment building in South-Western Sweden shows that by active usage of thermal mass a low energy consumption and high thermal comfort is achieved at a normal building cost.

Description of the project

The project called "Lärkträdet" is situated in the Swedish town Vara, around 100 km North-east of Gothenburg. The building was designed as a passive house (according to Passive House codes by Swedish Energy Agency) and planned for elderly persons (all people are above 75 years old) and was taken into operation in June 2010. The total area (Atemp)[2] is 1 242 m² of which 830 m² is living floor space. The basement consists of storage areas, one common area, heating and electrical equipment room (heat pump, etc) and four floors with apartments. On each floor there are four flats, two with a size of 50 m² and two with a size of 54 m². On the roof there is a terrace, solar panel installations and the mechanical plant room. See **Figure 1** and **Figure 2**.

Figure 1. External view from South-East.

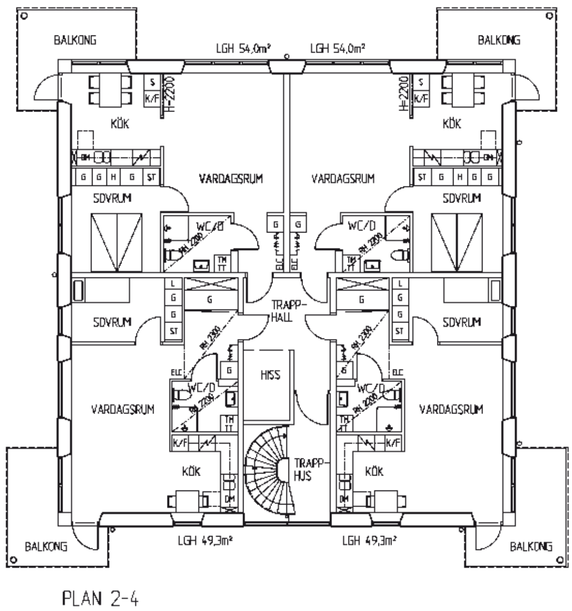


Figure 2. Floor plan.

Structural system

The building envelope consists of well-insulated and load-bearing pre-fabricated sandwich wall elements (150 mm concrete, 250 mm EPS, 70 mm concrete) supporting the floors of 200 mm deep hollow core concrete slab elements. The insulation thickness is the same practically everywhere as the slabs are supported on the inner

2 The area in m² is based on Atemp which is the total floor area measured inside the external wall heated to more than 10°C.

part of the concrete wall. Therefore, the cold bridges are very low. Other passive houses have normally an insulation thickness above 400 mm. See **Figure 3**.

The wall and slab are then cast together. This construction forms a very airtight building without having to use any tape for sealing of membrane joints. The ground floor slab consists of 250 mm concrete on top of 300 mm EPS insulation, The roof has an average insulation of 400 mm EPS. To verify the air tightness the Royal Institute of Technology pressure tested the whole building in May 2010. The result at a pressure of 50 Pa, was 0.27 l/s per m² of building envelope area.

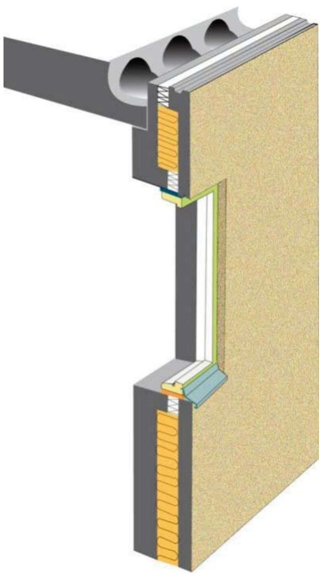


Figure 3. Facade element from Strängbetong.

HVAC system

The HVAC system consists of mechanical supply and exhaust air with a thermal wheel heat recovery unit. The building is using the TermoDeck system for ventilation, heating and cooling, where the supply air is passing through a labyrinth inside the hollow core slab before entering the room. See **Figure 4**. The AHU is placed on the roof. The supply air leaves the AHU at a temperature between 13 and 27°C depending on the outdoor temperature. There is a separate supply air duct from the AHU to each apartment which has a heating coil in the supply air duct placed above the false ceiling in the bathroom or entrance. There is also a short bulkhead in the bedroom. The rest of the supply air route sits inside the slab. The supply air temperature can be heated to maximum 49°C. The supply air flow to the apartments varies between 0.40…0.50 l/s, m² residential floor area.

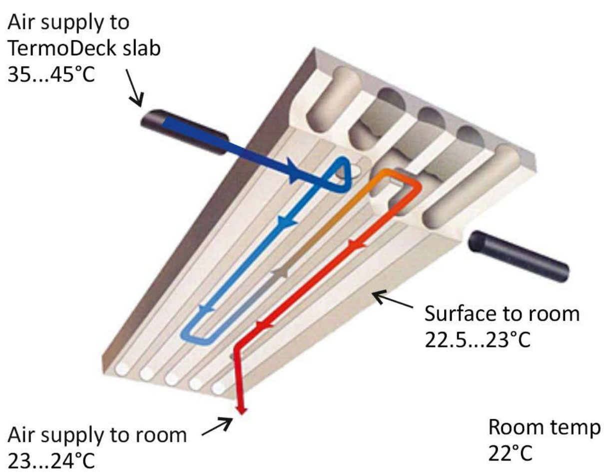


Figure 4. TermoDeck slab in heating mode.

The heating coil is regulated by a thermostat inside the apartment which allows the tenant to adjust the indoor temperature between 20 and 23°C. There are three supply air diffusers in each apartment, two in the living room and one in the bedroom. See **Figure 5**.

Figure 5. View from living room.

The exhaust air is removed from the bathroom. In the kitchen there is a separate exhaust from the cooker hood not connected to the AHU used when cooking food.

Each bathroom is equipped with an electric towel rail (connected to household electricity).

Heating and hot water system

Heating is generated from a ground source heat pump (8.4 kW electrical power with an estimated yearly COP of 2.7), designed to cover at least 90% of the energy consumption) which is complemented by an electric heating coil (9 kW) to be used as back-up and during the coldest period. The building has no radiators and the apartments are heated by hot air which can be supplied at a temperature up to 49°C.

16 solar panels with a total area of 37 m² facing West and South are installed to provide hot water. Around 50% of the hot water is designed to be generated from the solar panels.

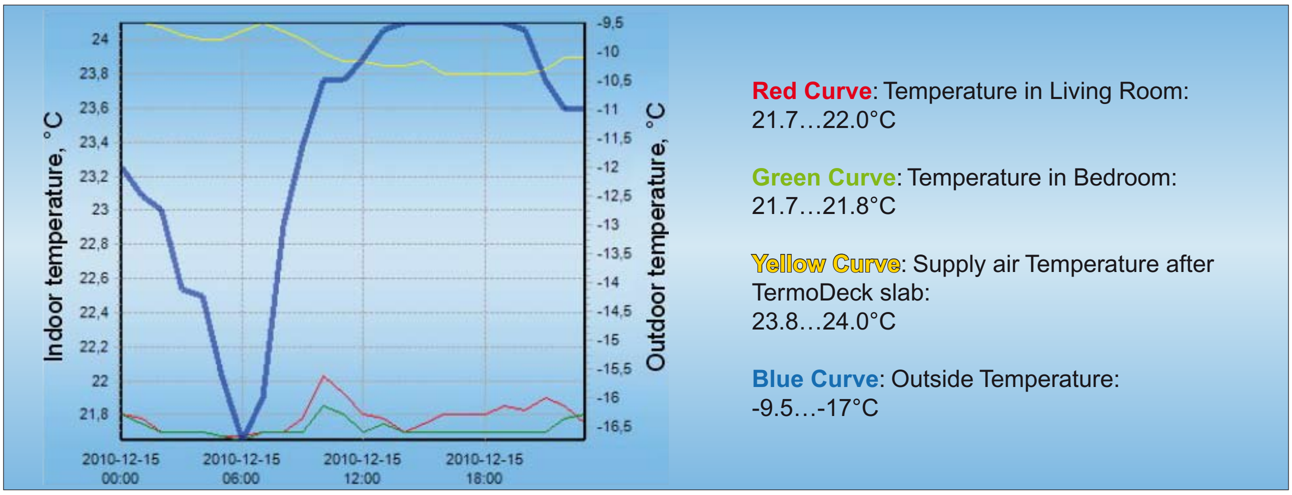


Figure 6. Temperatures in Apartment 3C facing North-East with supply temperature 42…48°C after the heating coil (into the slab). Scale for indoor temperatures on left and outdoor temperature on right.

Passive houses and thermal mass

Passive houses are built to reduce energy usage as they are well insulated, low infiltration rates and energy efficient HVAC-systems. However, they rarely have high thermal mass which in combination with high passive energy gains mainly from solar heat can lead to overheating and poor thermal comfort. Further, previous research shows that there are many advantages with heavy constructions such as lower indoor temperatures during the summer months and lower energy and peak power requirements.

In order not to exceed the mandatory requirement for passive houses of 10 W/m² of heating demand the window area cannot be too big and the insulation in walls (normally >400 mm), roof (normally >500 mm) and ground (normally >300 mm) must be quite thick. The wall thickness required depends to a large extent of the level of cold bridges.

How thermal mass is influencing the indoor thermal climate

As the TermoDeck system is used for ventilation, heating and cooling, the supply air (after its passage through the hollow core slab) is never above 24…25°C when entering the room even when the supply air to the hollow core slab is 49°C. See **Figure 6**. The risk of overheating the bed rooms is thus eliminated and a better and more even indoor climate is achieved as the heat is distributed more uniformly from ceiling and floor to the whole apartment. Warm surface areas also assure a high thermal comfort.

Overheating is also reduced as cool night air temperatures down to 13°C can be supplied which dissipates the heat accumulated during day time and cools down the slab making it possible to absorb heat the next day. Due to an incorrect adjustment in the air handling unit the minimum supply air temperature was set to 18°C. See **Figure 7**.

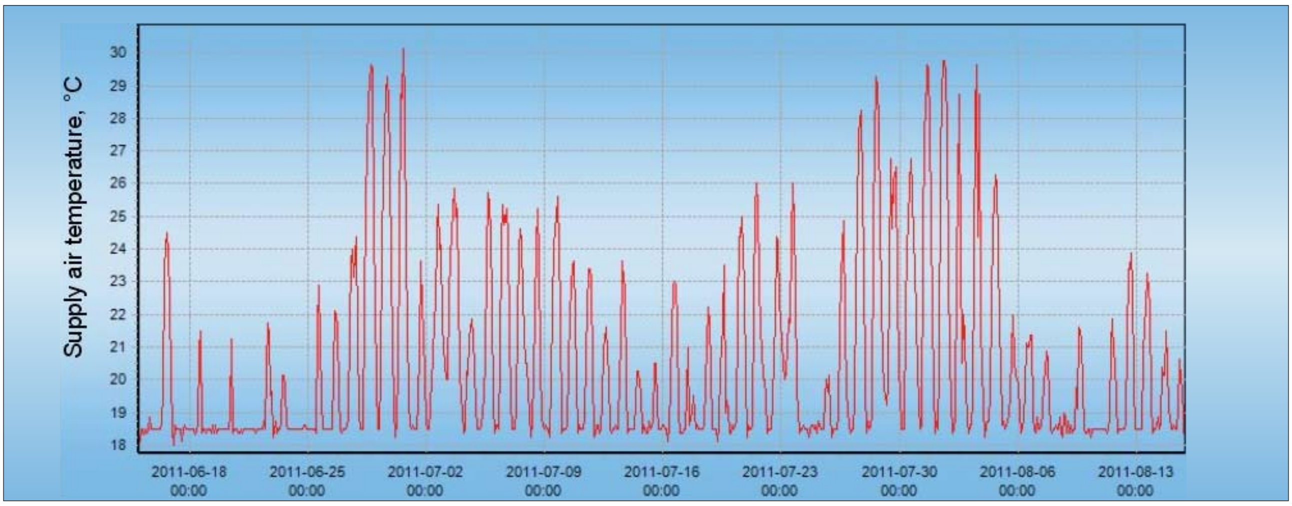


Figure 7. Supply air temperature.

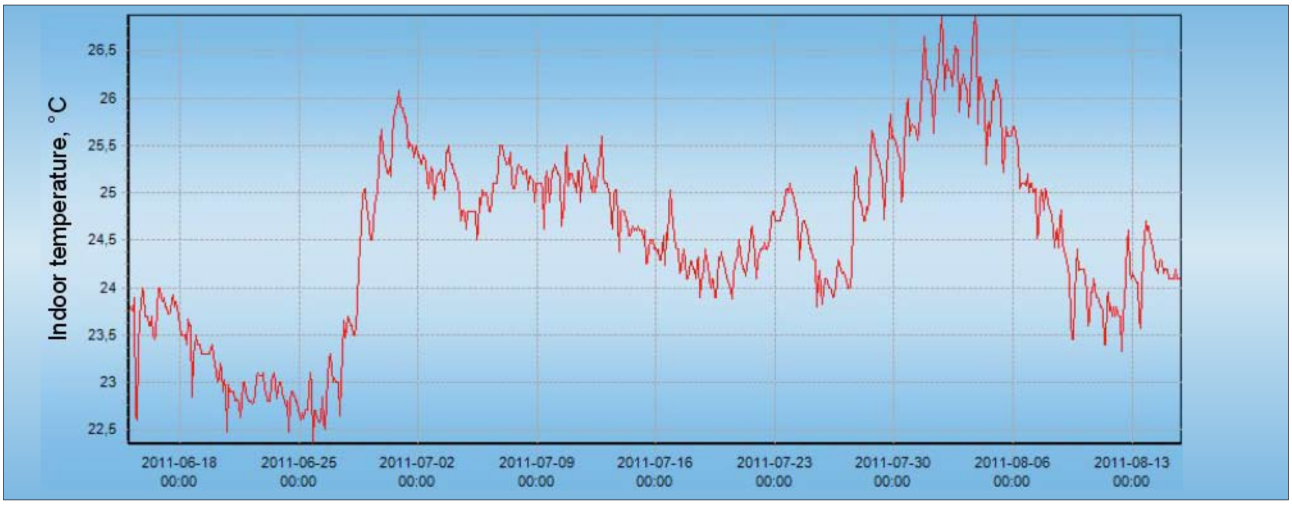


Figure 8. Indoor temperatures in Apartment 2A. Situated on the 1st floor. South-West orientation.

This was supposed to have changed during 2011 but the problem still exists. Despite this, the indoor temperature in a South-West apartment on the 1st floor has not exceeded 26°C for more than 90 hours during the year (well below the advice of 440 hours for Passive House codes). See **Figure 8**. The maximum temperature has never exceeded 27°C. The indoor temperatures in apartments facing NW and NE have never exceeded 26°C. The outdoor temperature was peaking at around 30°C during this period (the average outdoor temperature during July was 2°C higher than normal). During the hottest times, cold has been heat recovered from the exhaust air. In order to achieve these relatively low temperatures, the mid-pane blinds have probably been drawn and the tenants have probably opened the windows. When the AHU is adjusted correctly, the maximum indoor temperature is estimated to exceed 26°C for around 30…40 hours.

By using a well insulated and air tight building together with a high degree of available thermal mass (due to exposed concrete slabs and walls) the building's time constant is high (above 350 hours). The dimensioning outdoor temperature can therefore be reduced from -18°C down to -10°C according to the specifications for passive houses in Sweden

Comparison between heavy and light-weight building

A master's thesis – carried out at Mälardalens Högskola, Sweden - examined Lärkträdet. First, a theoretical model of Lärkträdet was created in the simulation software IDA Indoor Climate and Energy to conduct a preliminary mapping of its energy use. Then, the building frame was changed from its heavy original in concrete (not using TermoDeck) to a lighter version based on a wooden stud construction in order to compare how the building's indoor climate and its energy and power requirement would differ if the building was built using a lighter frame.

With a minimum temperature of 22°C in the whole building the energy consumption for heating was 7.4% higher for the wooden stud construction compare to the heavy construction according to the simulation.

In comparison with the wooden stud construction, the greatest advantage of the concrete construction was found to be its considerable better indoor climate. In the wooden stud construction the operative indoor temperature was outside of acceptable boundaries for a studied apartment unit in the building for almost four times as many hours (673 vs. 175) as in the concrete construction. The operative indoor temperature is also much more stable in the heavy building. An apartment with windows in South and West was studied. For example, in the light-weight building the indoor temperature is above 26°C even in March. (**Figure 9**).

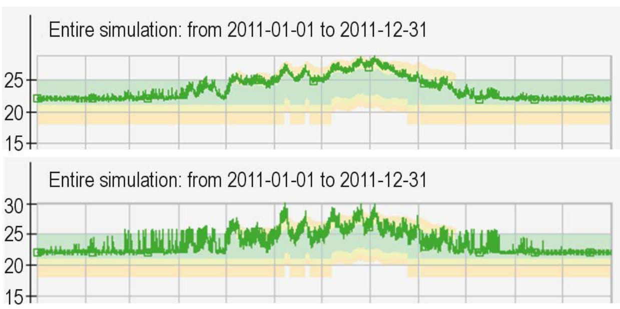


Figure 9. Simulated indoor temperature in the original concrete construction is more stable and comfortable (top) than in the building with light-weight wooden stud construction (below).

Energy consumption

Total purchased electrical energy was designed to be 30.5 kWh/m^2 (Atemp), year. For the first year, the measured value was 37.9 kWh/m^2, year. This value is continuously decreasing and for the period Dec 2010 to Nov 2011 the value is 33.1 kWh/m^2, year. (Each period is twelve months). The purchased electrical consumption between June and November 2011 has decreased by 25…40% on a monthly basis compared to the same period 2010. Normal year correction for heating has not been done. When item 4 is taken into account (2…3 kWh/m^2 reduction), the building has dried out and items 2, 6 and 7 (see under next heading) have been sorted out the total purchased electrical energy is expected to be around 28 kWh/m^2 for a normal year. See next heading and **Table 1** and **Figure 10**.

Differences between designed and real data

The input data used during the design of the project was compared to the real measured data. All simulations have been carried out with the software IDA Indoor Climate and Energy.

1. The efficiency of the heat exchanger was calculated to be 80% in the design. When measured it seems to be around 73%. Simulated yearly increased **heating** consumption: **2.5 kWh/m^2** (Atemp). (Not expected to be reduced).
2. The room thermostats were originally installed from the manufacturer on a range from 17...27°C leading to high indoor temperatures (above 23°C) during winter. This was changed to maximum 23°C in June 2011. However, indoor temperatures have still been above 24°C in October 2011 so the thermostats don't seem to work properly (as the heating coil is still on). Indoor design temperature was 21°C.Simulated yearly increased **heating** consumption: **2...3 kWh/m^2**.

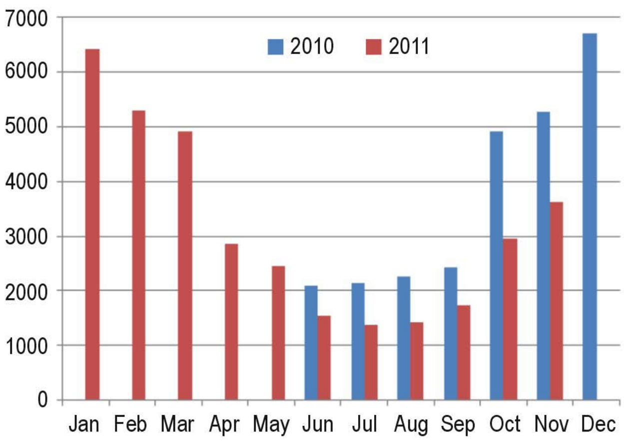
Table 1. Electrical Energy Consumption divided on different energy meters (kWh/m^2, year) on 2010-2011.

	July-June	Nov-Oct	Dec-Nov	Expected
Ground Source Heat Pump	17.9	16.8	16.1	13.5
Electric Coil for Water tank	5.6	3.3	2.8	1.9
Fans	5.6	5.6	5.6	5.6
Property Electricity[2] (excl. fans)	8.8	8.7	8.6	7.0
Total Purchased Electrical Energy[3]	37.9	34.4	33.1	28.0

2 Property electricity is the electricity paid for by the landlord (for lifts, common areas, lights in stair ways and outdoor, etc).

3 Purchased electrical energy includes all energy used by the property except the household electricity that is paid for by the tenants (lights, electrical appliances, etc).

3. Internal heat gains are less than the specifications for passive houses used for the simulation. The household electricity has been measured for each apartment. There are 16...17 persons living in the building. Simulated yearly increased **heating** consumption: **3.5 kWh/m^2**. (Not expected to be reduced)
4. Actual mean outdoor temperature during the first heating season is 3°C less than the weather year used for the simulation. Simulated yearly increased **heating** consumption: **5...6 kWh/m^2**. (This will vary from year to year). Compared to a normal year the consumption would decrease by **2...3 kWh/m^2**.
5. The SFP of the fans is measured to 2.0 kW/m^3,s. It was designed to be 1.6 kW/m^3,s. Calculated yearly increased **electrical** consumption: **1.0 kWh/m^2**. (Not expected to be reduced).
6. An electric coil placed outside the heat pump used to heat up the hot water in the hot water tank was used excessively. When the hot water circulation was stopped (after 7 months) the electrical consumption was heavily reduced from 900 down to 300 kWh per month. Estimated yearly increased **electrical** consumption: **3.7 kWh/m^2.**



Temperature Design Data:

* Design Winter Outdoor temperature: -18°C
* Design Summer Outdoor temperature: 27°C
* Designed Mean Annual Outdoor temperature: 7.0°C
* Actual Mean Annual Outdoor temperature (Oct 2010 – Sep 2011): 6.0°C
* Designed Mean Outdoor temperature during heating season (Oct – Mar): 1.5°C
* Actual Mean Outdoor temperature during heating season (Oct 2010 – Mar 2011): -1.5°C
* Indoor design temperature: 21°C.

Figure 10. Purchased Electrical Energy Consumption during 2010 and 2011 (kWh).

7. A leaking pump in the basement has led the pump to work for several hours each day. This is reported to have been solved on Nov 10 2011.Estimated yearly increased **electrical** consumption: **1.7 kWh/m².**

Construction costs

The total construction cost for Lärkträdet is around 19 350 SEK per m² of residential floor area excl. VAT. It is difficult to compare against other conventional buildings as the cost depends on several aspects such as type of contracting form, size of project, areas included in the price (parking places, common areas, etc), choice of standard in bathrooms and kitchens. However, the cost increase does not seem to be higher than maximum 5% compared to conventional building costs (using water radiators and less insulation).

Conclusions

- The measurements from Lärkträdet shows that the indoor temperature is very similar in different rooms within the apartments all year around.
- The active usage of thermal mass leads to:
  - An even temperature throughout the apartment without risk of overheating
  - Very stable indoor temperatures also during hot and cold periods
  - Few hours with high temperatures during summer months
- The passive house requirements can be achieved with 25.0 mm insulation in the walls if cold bridges are kept low.
- Low energy multi-family residential buildings don't have to cost much more than conventional designs. 3E

Project data

Name: **Block name "Lärkträdet"**

Location: **Allegatan 24, 534 32 Vara, Sweden**

Function of the building: **Apartment building**

Developer and Owner: **Vara Bostäder AB**

Architect: **Vara Byggkonsult AB**

Contractors:

Main contractor: **Tommy Byggare AB**

Sub-contractor: **AB Strängbetong** (as for the building frame and envelope including TermoDeck.

Total Area: **1 242m²** (830 m² of residential floor area divided on 16 apartments).

Building envelope area: **1 339 m²**

Windows from the wall area: **16%**

U-values of construction components

Building Components	U-values
Facade Wall (including cold bridges)	0.21 W/m², K
Basement Wall	0.18 W/m², K
Ground	0.12 W/m², K
Window incl. frame	0.90 W/m², K
Roof	0.087 W/m², K
Infiltration	0.27 l/s, m² of Building Envelope Area at 50 Pa
Average U-value ((incl. cold bridges)	0.27 W/m², K

Passive houses in Sweden

Requirements of Passive Houses according to codes by Swedish Energy Agency:

- U-value of windows should be at least 0.9 W/m², K
- Air leakage rates of 0.30 l/s per m² façade at 50 Pa
- Heating demand at dimensioning outdoor temperature (DUT) shall be max 10 W/m² (for Southern Sweden).

Advice:

- The maximum yearly energy consumption is 60 kWh/m². (This figure is reduced to 30 kWh/m² if electricity is used for producing heating and hot water – such as using heat pumps, etc. This figure includes everything except household electricity used by the tenants).
- Heat Exchanger Efficiency (including losses in shafts, due to unbalanced air flows, etc) of at least 70%.
- Indoor temperature from April to September shall not exceed 26°C more than maximum 10% of the time (=440 hours).
- The ventilation system should have an SFP-value of maximum 1.5 kW/(m³/s).
- Property electricity shall be maximum 10 kWh/m².
  (The m² area is the total area= Atemp)