A prototype architecture for passive and plus energy building in Estonia

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Abstract

The project serves the goal of providing an example of an architectural interesting house which realizes the capacity the passive house concept as well as of extensive passive and active solar techniques. The building should demonstrate that it can produce the same amount of energy than is needed over the year - even in northern countries. A progressive architectural concept was used to create a model single-familiy building: it is based on the passive house idea, using the energy of the ground and of the sun (thermal active, passive and PV). Since the winter sun has to contribute a big part of the heating of the house the south side of it is opened with big windows. This goes back to the fact that just in the south façade windows can give a positive balance over the heating season (and not windows at other orientations). Like a second façade and a second skin a simple construction overlaps the southern façade and the roof. This construction helps to keep the south side of the house at summer in shadow. This second façade carries above the roof 90 m^2 of photovoltaic panels. On the northern side of the roof integrated slanted thermal collectors (12 m^2) give space for a natural summer ventilation system for the house (beside of the summer the ventilation is done with the usual mechanical passive house ventilation system). Those roof collectors are optimized for the summer sun (warm water production). Integrated in the façade thermal collectors are optimized for the winter operation (13 m^2 for heating and warm water). Those vertical collectors gain special profit from the deep inclination of the winter sun and from the permanent snow reflection at this time. Prototype architecture for Estonian conditions demonstrates that even in a cold northern climate it is possible to build energy productive houses. Main attention should be on aspects to reduce heat losses.

Keywords: solar optimized design, solar heat gains, passive house standard, photovoltaic

Introduction

The building described in this paper uses the passive house concept for a Nordic country and should serve as a model for passive and plus energy buildings in northern latitudes. The building is housing for a typical Estonian family with 5 members and should demonstrate that a passive house concept combined with active solar technologies can produce same amount energy than is needed over the year - even in northern countries.

Climatic conditions

As a typical country bordering the Baltic Sea, Estonia is divided to two climatic zones – e.g. coastal area and inland area where conditions differ due to influence of nearby sea. The more detailed spatial division and climatic differences are given in [Kalamees and Vinha 2004]. The building described in this article is located in the town of Põlva at the South-East part of Estonia where more continental climatic conditions occur along with lower temperatures, deeper and longer lasting snow cover compared to coastal areas [Raik 1967 *cited in* Kalamees and Vinha 2004]. Compared to Central European climate where the use of passive and active solar techniques are more widely used the winters are cold in Estonia. Based on national Test Reference Year for energy calculations the long-term average dry bulb temperature for inland part of Estonia in December is -2,5°C, in January -3,0°C and in February -5,2°C [Kalamees and Kurnitski 2006], however long-term average daily minimum values for each month from November to March are below -10,0 °C reaching -14,3 °C for January [Kalamees 2006].

In more extreme years the air temperature falls below -30 °C occasionally, staying frequently below -15 °C for several days [Estonian Meteorological and Hydrological Institute 2002]. Despite the low temperatures there are also a lot of solar radiation available on Southern elevations on cold days (especially in February and March) due to lower solar altitudes and long lasting snow cover compared to Central European locations. Though the monthly sums of direct and indirect solar radiation on vertical surfaces strongly depend on the yearly variation of snow and cloud conditions [Estonian Meteorological and Hydrological Institute 2003], the nearly perpendicular sun-angles in heating period make the solar use strategy in this latitude (58°N, 27°E) interesting.

Project description

Architectural solution

The building site is a rectangular plot with two different levels. The new building is positioned within the given slope connecting those levels leaving the south and east façade of basement floor exposed to winter sun. The main glazed façade is oriented directly to south maximising the use of passive solar gain during the heating season. On southern façade terraces and balconies are partly reaching out over the slope to give shade and protect against the overheating during the summer period.

Figure 1 Rendered view and photos from building time.

The building has three stories, total net floor area of 305 m^2, external envelope surface area of 864 m^2 and enclosed volume of 1586 m^3, which corresponds to compactness factor A/V of 0,55 m^{-1} for the building. For the energy calculations a reduced “treated floor area” of 280,6 m^2 was used (40% of rooms with no windows and corridor in the basement was excluded).

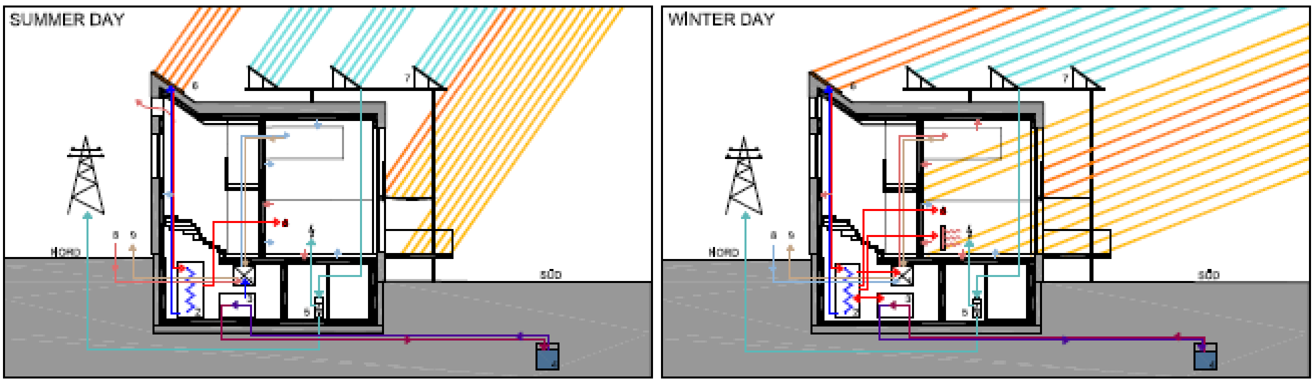

Figure 2 Cross section of the building. Summer situation on the left and winter situation on the right graph.

The ground level consists of an entrance area, the big living room, the kitchen, the master bedroom and the corresponding auxiliary rooms. The living room is two stories high and is facing the south with a generous glass façade. In the upper floor you find a gallery, which is open to the living room and gives access to three children's bedrooms and a working area. In the basement there is a sauna and a steam bath (both very important in the daily day live of the inhabitants) connected with an area for shower and a big room for recreation (fully served with day light). There are also a technical room, a room for the kids and some storage rooms.

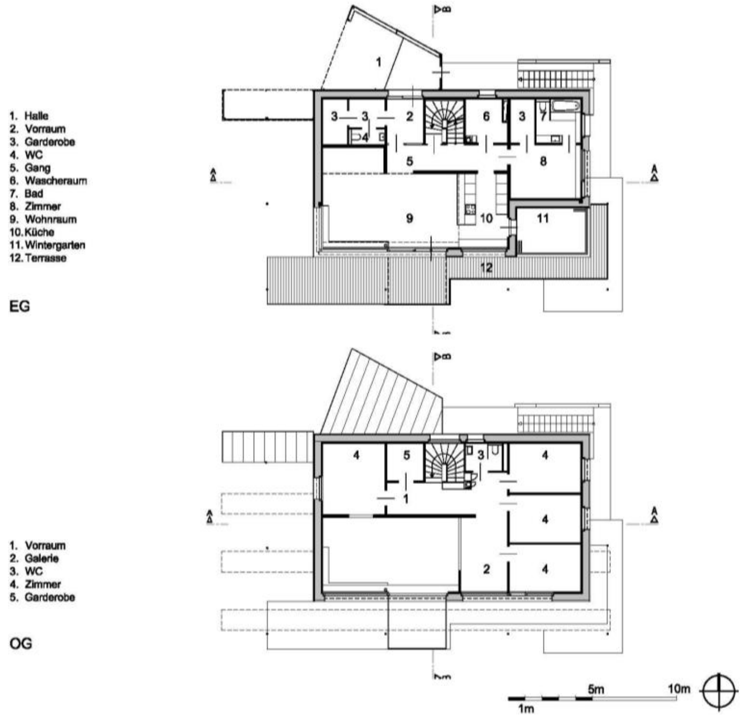

Figure 3 First floor plan (above) and the second floor plan (below).

Since the winter sun has to contribute a big part of the heating of the house the south side of it is opened with big windows. This goes back to the fact that just in the south façade passive house quality windows can give a positive balance over the heating season (and not windows at other orientations).

Separate lightweight construction is built over the building to support the large array of photovoltaic panels (90 m^2), which provide a source for renewable energy and at the same time provide additional shading for the roof and southern façade.

Special slanted extension of the roof construction on the northern side is created to allow additional night cooling through natural ventilation. The extension also gives support and thermal resistance for roof integrated solar thermal collectors (11,6 m^2 active surface area). Those roof collectors are optimized for the summer sun (warm water production). Additionally, a separate array of solar thermal collectors (13,1 m^2 active surface area for heating and warm water) are integrated to southern façade and optimized for the winter operation. Those vertical collectors gain special profit from the deep inclination of the winter sun and from the permanent snow reflection at this time.

Thermal envelope

The house is built with mixed construction system – the basement (partly in ground and partly open to the sloping hillside) is casted concrete construction with thick layer of XPS/EPS insulation depending on the wall/floor type. The aboveground perimeter walls have 300 mm of EPS insulation and belowground perimeter walls have 500 mm of EPS insulation. The floor slab configuration features 300 mm of XPS insulation and 100 mm of EPS insulation.

Ground floor and upper floor have a 94 mm thick cross-laminated timber block elements (KLH) as the static layer and 400 mm of cellulose insulation with custom made C-joists made out of timber and OSB sheets. The roof panel is insulated with wedge shaped EPS insulation (380 mm - 550 mm). The walls of the upper floors have façade solution with ventilated cavities mainly covered with rendering boards and partly covered by vertical solar collectors.

Special construction was applied to unheated (but inside building's rectangular form) conservatory floor, which needed 80 mm of vacuum insulation panels (Vacupor Vacuspeed) to achieve the needed thermal resistance and also lower the thermal bridges in surrounding junctions.

The glazed areas feature krypton filled triple glazing with different low-emissivity coatings depending on the orientation of the windows and glazed doors. The declared Ug values of the glazing units are 0,60 W/(m^2K) for the southern façade and 0,49 W/(m2K) for other orientations, the SHGC values for these glazing units are accordingly 0,59…0,62 for southern façade and 0,36…0,37 for other facades depending on the glazing thickness. The glazing properties are differentiated to maximize the solar gain during the heating season. The wooden window frames with thermal separation (SmartWin) have very low thermal conductivity (average Uf value for openable windows 0,75 W/(m^2K) and 0,59 W/(m^2K) for fixed windows) to minimize the heat losses.

Additionally all possible measures were taken to lower the heat losses including the optimization of thermal bridges. The thermal bridging in main junction types were avoided by the selection of construction type with uniform outside insulation. However, the bulk amount of different window connection details were calculated with LBNL Therm software to achieve as good as possible solutions for regular installation, but also for fixing the shading rolls on southern façade. Almost all possible junctions were assessed with 2D finite element calculation in order to gain all possible reductions in heat balance calculation. An overall reduction by 1,9 kWh/(m^2yr) to annual net heat demand was achieved compared to situation with no thermal bridge input using external dimensions.

In total the average thermal conductivity of the whole building envelope (including windows, doors and linear thermal bridges) is 0,146 W/(m^2K).

Ventilation system

The building has balanced mechanical ventilation system with PHI certified passive house ventilation unit (Paul Novus 300 with exhaust side heat recovery efficiency 93% according to PHI certification system) [Passivhaus Inst 2009]. Fresh air with no additional heating is supplied to living-room and bedrooms and then exhausted from kitchen, bathrooms. The airflows have been reduced to limit the risk of overly dry air during the winter season. The average airflow rate measured during the startup of the ventilation system is 280 m^3/h, which corresponds to average air change rate of 0,4 h^{-1}.

Preliminary measurements show that CO_2 levels are low enough to further lower the airflows if necessary.

The frost protection of the ventilation unit is solely by sub-soil brine heat-exchanger. The system features 226 m (with 40 mm diameter) of plastic pipe buried horisontally in the depth of approx 1,0 to 1,2 m and connected to Paul Sole Defroster unit SD-550, which controls the fluid flow speed of the system according to air-temperature before the ventilation unit. Preliminary measurement results show stable air temperatures around 1°C after the defrosting unit for the first heating period.

The infiltration and exfiltration of the air through the building envelope is reduced radically through the use of special airtightness products and careful planning and execution. Measured average airtightness at the 50 Pa pressure difference (average air change rate n_{50} of the under- and overpressurization test) is 0,36 h^{-1}.

Heating system

The heating system is based on ground source heat pump combined with split solar thermal system. Wiessmann "Vitocal 300 G BWC" ground source (two 80 m deep vertical boreholes) heat pump unit with 5,9 kW heating power output and declared (EN 14511) COP of 4,51 (for B0W35 conditions at flow/return difference of 5K) is combined with Sonnenkraft roof-mounted (11,6 m^2 active area) and vertical wall-mounted (13,1 m^2 active area) solar thermal panels and 2 x 1000 l storage tanks (PSC1000E). The panels are oriented directly to south. The storage tanks are covered with 200 mm insulation to reduce the stand-by heat losses and lower the overheating of the rooms on the basement floor.

A very short DHW circulation system with connected distribution pipes as well as piping from storage tanks to wall- and floor-heating collectors are insulated with 40 mm mineral wool or 13 mm Armaflex technical insulation depending on the placement of the piping.

The heat is distributed through water based wall- and floor-heating system with supply and return temperatures of 39/33 °C. The wall-heating system was chosen to lower the fluid temperatures and provide more uniform temperature distribution for greater indoor comfort.

Grid-connected PV system

The system consist of 66 panels SolarWorld Sunmodule Plus SW 196 Vario poly with unit dimensions 1001 x 1357 mm. The total panel area is 89, 8 m^2. Maximum power P_{max} under standard test conditions (STC) is 196 Wp. The panels are located in 3 rows, 22 units in each row (figure 4). Tilt angle from horizontal is 38°.

Figure 4 Roof with mounted PVs. Solar thermal collectors on the left.

Inverter is Solutronic Solplus 100, 11 kW, 98% efficiency. The system has Solutronic Loger with LAN output. Maximum output AC is 11000 W.

According to PVGIS calculation (Photovoltaic Geographical Information System for Europe) [ECJRC Institute for Environment and Sustainability 2013], the annual production of the system is 10120 kWh (setting 5% losses).

Heat balance of the building

The heat balance and subsequent net energy demand for space heating was calculated using PHPP2007 software (ISO 13790 monthly method). A detailed energy model was generated carefully describing all different envelope areas, lengths of the linear thermal bridges (calculated separately with finite element calculations) the shading situation etc.

Average climate data for Southern part of Estonia was selected from the default database in calculation software. The description of the usage (number of people, use of household appliances, energy demand for technical appliances etc) and internal gains was carefully estimated, which corresponded well with the conservative standard usage defined by Passivhaus Institute (average internal heat gains 2,1 W/m2) [Passivhaus Inst 2012]. Consumption of DHW (25 l/(d pers)) and heating setpoint temperature (20 °C) for Passive House certification were also defined according to standard usage.

Throughout the projecting phase and also in building process the heat balance of the house and its several configurations was iteratively calculated to optimize the room layout, insulation thicknesses, required efficiencies of the technical equipment and especially the configuration of glazed areas regarding their size, fragmentation and thermal and solar transmittances in order to fulfil the passive house requirements defined internationally. The final (as built) heat balance of the building for the heating period is given in the figure 5. The estimated annual net space heat demand of the building is 4043,8 kWh/a, which corresponds to specific net space heat demand of 14,4 kWh/(m^2a).

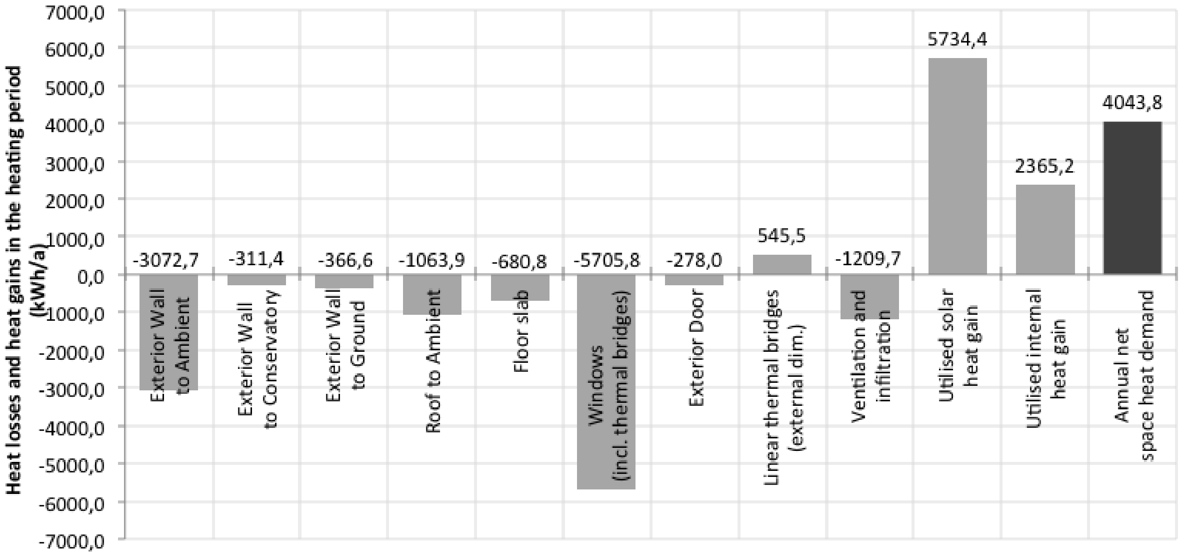

Figure 5 Heat balance of the building (as built) for the heating period.

From the Figure 5 it can be seen that heat loss through ventilation and air leakages is very small, which is achieved through the use of very efficient ventilation heat recovery system combined with ground-coupled brine preheating unit and good airtightness of the building envelope.

The heat loss through the highly insulated roof and floor construction is also quite small. The remaining heat loss through external wall (to ambient and also to unheated conservatory) has a lot more influence on heat balance. Although the thermal transmittance of the glazing units and also window frames are radically reduced using almost best components available on the international market, the windows are still the largest source of heat loss through the building envelope. The heat losses through windows and doors are more than all other sources of transmission heat losses altogether. This can be attributed to extensive glazing area on the south façade and also to few larger windows on eastern and western façade. Nevertheless, the large areas of glazing are a result of project optimization towards the energy efficiency. The losses through transparent envelope areas can be largely compensated by solar heat gains during the heating period even in the cold climate of Estonia. The separate heat balance of window areas for heating period (i.e. for the months that have calculated heat demand in this building) is given in the figure 6.

The calculations showed that using windows with high solar transmittance and very good thermal resistance resulted to overall heat gain in the heating period. The balance of heat gains and losses for the eastern and western windows showed that although a large part of combined heat losses can be compensated by the solar gains, the configuration still results in total loss because of the high latitude and low sunshine duration during the heating period. Therefore, to minimize the total heat loss, the thermal resistance of eastern, western and northern windows were maximized through the use of very low emissivity coatings in the glazing units, disregarding the solar transmittance of the glazing. This allowed to achieve higher utilized solar heat gains for total glazing area compared to the total heat losses through the overall glazing area in the heat balance shown in the figure 5.

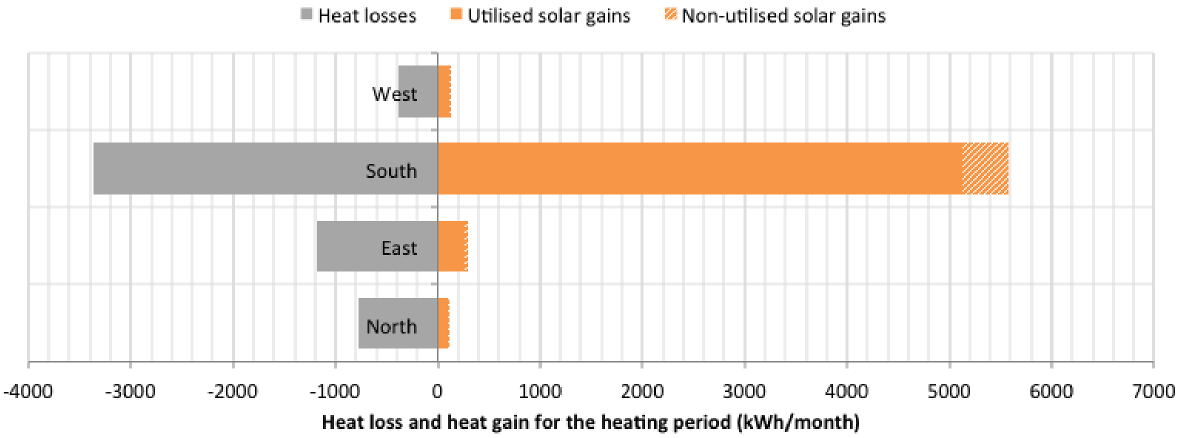

Figure 6 Estimated heat balance of the windows for the heating period.

The monthly figures of total heat loss compared to utilized and non-utilized solar and internal heat gains are shown in the figure 7. It can be seen that for the deepest winter months (November, December and January) the solar gains are low in such high latitude and cold Estonian climate, but already in February the solar gains surpass the remaining heat demand. For all other months in a typical (average) year all heat losses are compensated by internal and solar heat gains so no remaining space heat demand occurs. The extensive part of non-utilised solar heat gains in spring and summer period reduced by using external shading blinds on southern façade and night cooling through automatically induced natural ventilation (the shading and night cooling effect is not included in calculation results shown in figure 7).

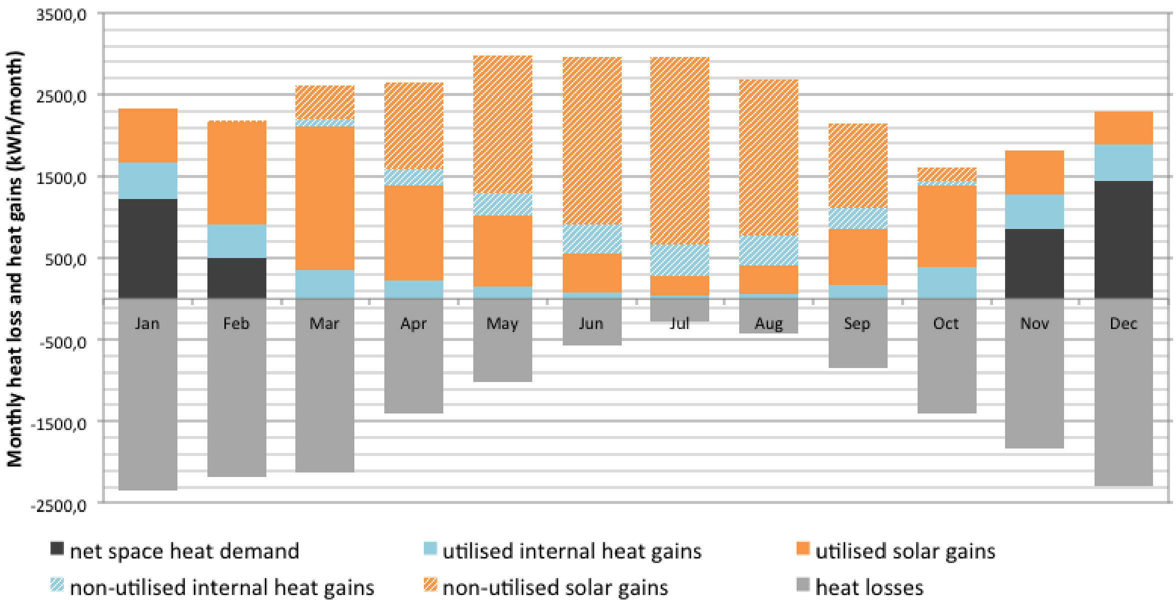

Figure 7 Estimated monthly heat losses and gains of the building (the effect of external movable shading elements are not taken into account for the summer months in this figure).

Final energy demand

Additionally to the heat balance and net space heat demand the heat losses of the heating system as well as domestic hot water system was calculated using PHPP2007 software package. Separately, the useful heat production of the solar thermal system was calculated using dynamic TSol calculation software by Sonnenkraft engineers. The useful heat demand for space heating and hot water production along with contributions of solar thermal as well as ground source heat pump system is given in figure 8. It can be seen that non-utilised heat losses from domestic hot water storage and distribution system have a big impact on total energy demand in the building when the energy demand of the building itself is radically reduced. This is mainly related to long pipe network, but also to 2000 l storage system of solar thermal system, which has large surface area due to its size. The solar thermal system provides approximately 43% of useful energy for total heat demand in the building.

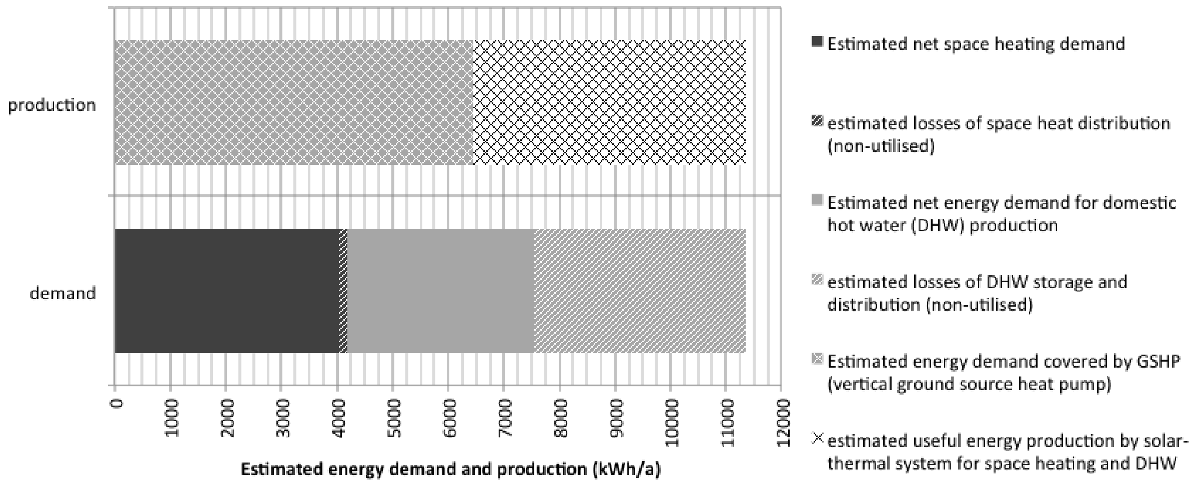

Figure 8 The useful heat energy demand of the building (including storage and distribution losses) and contribution of combined heating system.

In the end, the final energy consumption of the building was estimated for heating system, household appliances, lighting, technical appliance etc based on standard usage. The necessary solar PV collector area was optimized to cover the final energy demand on a typical year. The electricity production of the PV system was estimated with PVGIS calculator using detailed configuration of the built system. As can be seen in table 1, the estimated final energy (electricity) demand of the building is approximately 10400 kWh/a, which corresponds to specific final energy demand of 37 kWh/(m^2a). The solar PV system produces approximately 10120 kWh/a, which nearly covers the total demand and shows that building a net-zero energy house is possible in Estonian climate.

Table 1 Estimated final energy (electricity) consumption and production of the building

	kWh/a
Estimated electricity production by solar PV (photovoltaic) system	**10120**
Total electricity demand of the building	**10356**
including electricity demand of GSHP (vertical ground source heat pump)	2149
including estimated electricity demand of technical installations (ventilators, pumps etc.)	2000
including estimated electricity demand of domestic appliances, lighting, sauna equipment etc.	6207

Monitoring

After completion in February 2013 the building has been equipped with extensive monitoring system to gather information about indoor climate and performance of building system as well as external wall construction. The air temperature, relative humidity and CO_2 levels are monitored in several rooms, air temperature and relative humidity is monitored in ventilation system (air intake, preheated, supply, and extract airflows). Additionally energy consumption of heating system is measured along with solar thermal and solar PV system performance monitoring. Separately the external wall and massive clay partition wall layers are monitored.

Conclusion

The built project shows that through iterative calculation and design process a architectural solution is created, which allows extensive use of passive solar energy through the south facing glazed façade. The use of excellent building components along with favouring architectural solution radically reduces heat losses, which makes it possible to cover the entire energy demand of the building with renewable sources enabling to create net-zero energy building with the help of grid connected solar PV system. Maximizing the solar heat gain in the heating period, while keeping the transmission heat losses through the glazed areas is crucial when targeting the internationally defined passive house criteria in Nordic climate region.

Data and Project Participants

Object address: Metsa 5a, Põlva, Estonia. Owner: Kuldar Leis.

Architects: Martha Enriquez Reinberg and Georg W. Reinberg, Architekturbüro Reinberg ZT GmbH, Wien, Austria.

Treated floor area according to PHPP: 285 m²; Volume 1222 m³

Construction time: October 2011 – February 2013

Consulters: Tõnu Mauring, Jaanus Hallik and Kristo Kalbe, University of Tartu (building physics, monitoring), Johannes Riebenbauer, Graz (static engineer), S&P Climadesign GmbH (technical systems), Margus Valge, Sense OÜ (project management and site supervision), PassiveHouse OÜ Estonia and Passive House Institute, Darmstadt (certification).

References

[ECJRC Institute for Environment and Sustainability 2013] PVGIS: a web- based solar radiation database for the calculation of PV potential in Europe (available online: http://re.jrc.ec.europa.eu/pvgis/apps4/pvest.php?lang=en&map=europe)

[Estonian Meteorological and Hydrological Institute. 2002] Raw measurement data at three-hour steps over the period from 1970 to 2001 in Tõravere weather station.

[Estonian Meteorological and Hydrological Institute. 2003] Handbook of Estonian solar radiation climate. 2003

[Kalamees, T. 2006] Hygrothermal criteria for design and simulation of buildings. Thesis, Tallinn University of Technology.

[Kalamees, T. and Kurnitski, J. 2006] Estonian test reference year for energy calculations. Proceedings of the Estonian Academy of Sciences. Engineering 12 (1): 40-58.

[Kalamees, T., Vinha, J. 2004] Estonian Climate Analysis for Selecting Moisture Reference Years for Hygrothermal Calculations. Journal of Thermal Envelope and Building Science 2004 27: 199 (2004)

[Passivhaus Inst 2009] Requirements and testing procedures for energetic and acoustical assessment of Passive House ventilation systems for Certification as “Passive House suitable component”, Passivhaus Institut (2009)

[Passivhaus Inst 2012] Certification criteria for residential Passive House buildings, Passivhaus Institut (2012)

[Raik, A. 1967]. Eesti klimaatilisest rajoneerimisest. Eesti Loodus, 2: 65–70.