Passive Solar House in Croatia

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Abstract

Passive solar house covers its energy requirements, partially or completely, utilizing solar energy, by means of active and passive systems. In spite of great advantages that a passive solar house offers, only a few of them have been built in Croatia ever since. Heat losses and heat gains calculations have been made to estimate the necessary thickness of thermal insulation as a function of window surface size, weather data and solar irradiation for several locations in the coastal and continental area of Croatia. The household demands for thermal and electrical energy are implemented in the calculations in order to determine the necessary size of solar conversion systems: collectors and PV cells. It has been concluded that passive house standards are met with 20 to 35 cm of thermal insulation in the coastal area and islands, whilst the insulation has to be as large as 40 to 60 cm in continental and mountain regions of Croatia. It has been determined that just 5 to 7 m^2 of solar collectors could provide most of the necessary energy for water heating. However, to ensure most of the electricity for household appliances, 40 to 90 m^2 of PV cells should be installed on a passive house. Enlarging the solar collector area to about 10 m^2 and providing a heat storage tank, considerable fractions of space heating energy demands could be supplied by appropriate solar combisystems. A combisystem with 9 m^2 of solar collectors and a small ambient air-to-water heat pump could supply 80% of the annual heating energy demand and save 47% of the primary energy in a passive house in the City of Rijeka.

1. Introduction

Croatia is going to access the EU in the near future and by that the "20/20/20 by 2020" plan will become an obligation to fulfil. Such ambitious goals can not be achieved without broader intervention in the largest sectors-consumers of energy in Croatia: buildings and transport. Nowadays, Croatia faces energy squandering in buildings: of the total primary energy consumption in Croatia, 18.2% is consumed in households [1]. About 10 000 new buildings are being constructed every year in Croatia but only few of them are built with passive house standards. Paradoxically, large amounts of solar energy (1100 to 1600 kWh/m^2a) and the favourable climate offer substantial opportunities for Croatia to build passive solar houses [2-3]. The goal of the paper is to determine the necessary thickness of thermal insulation and the optimal size of south-oriented windows in order to reach passive house standard energy consumptions in detached single-family houses for several major cities of Croatia. Also, the necessary size of solar conversion systems (solar collectors and PV cells) to alleviate the demand of conventional energy sources is calculated. Specifically, solar combisystems combined with heat pumps present good opportunities for supplying both heating and cooling energy in passive houses and its performance has been tested for a passive house in the City of Rijeka.

2. Croatian passive solar house design features

2.1. General input data

The detached single-family house has a shape factor of 1 and a mean building envelope *U*-value from 0.1 to 0.15 W/m^{2}K, depending on geographical location. The net floor area of the house is 100 m^2 and the number of occupants is 4. Heat gains from internal sources are set to 2.1 W/m^2. The south-oriented windows have an area between 5 and 20 m^2. All windows have triple glazing and low-*e* coatings that results in mean (frame and glass) U-value of 0.7 W/m^{2}K. The window solar radiation transmittance is 60%. The frame ratio in the windows is 15%. To satisfy indoor natural illumination requirements, the window area on east- and west-oriented façade is 3 m^2. Wall, floor and roof thermal bridges are taken into account with a contribution of 0.01 W/m^{2}K in the mean envelope U-value. The passive house air infiltrations are supposed to be equal to 0.05 ach and room air quality is maintained with mechanical ventilation system operating at a minimum constant value of 0.4 ach (25 m^3/h of fresh air per occupant) in winter period. The mechanical ventilation system is equipped with a heat recovery operating at 70% efficiency when ambient temperature is below 12°C. When ambient temperature takes values between 12 and 18°C the ventilation system bypasses the heat recovery. When the ambient temperature rises over 18°C the ventilation system switches to 1 ach to prevent indoor overheating. No special shading contribution from solar blinds and curtains or summer night ventilation strategies are implemented in the calculation, but average monthly shadings from the south-oriented roof overhang have been taken into account. It has been established that best roof overhang effects on space cooling energy consumptions results when the roof overhang length is 3 m and the headwall height 1 m, for window height of 2 m. Prior to calculations, the space heating and cooling energy demands from average monthly weather data were compared with hourly-based calculations from test reference year [4] for the City of Rijeka in order to determine the level of agreement, Fig. 1. For that purpose, the mean building envelope *U*-value is 0.15 W/m^{2}K and the south-facing window area is 10 m^2, the thermal insulation thickness is 320 mm (*k*-value of 0.04 W/mK). Weather conditions in Rijeka result with design ambient temperature of -4°C, 2045 heating degree-days, 25 cooling degree-days (base temperature 26°C) and 1350 kWh/m^{2}a of solar irradiation on horizontal surface.

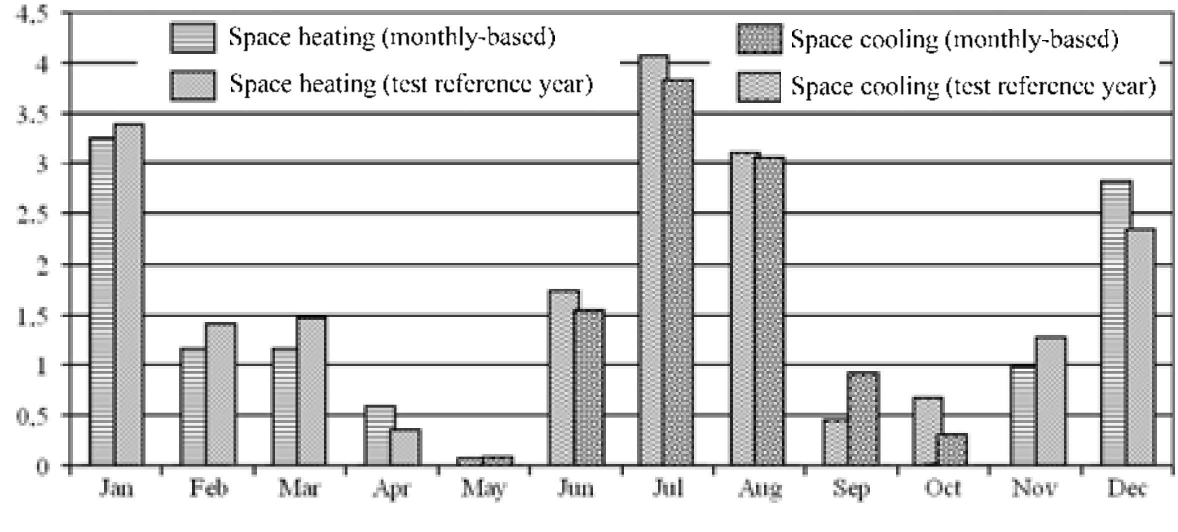
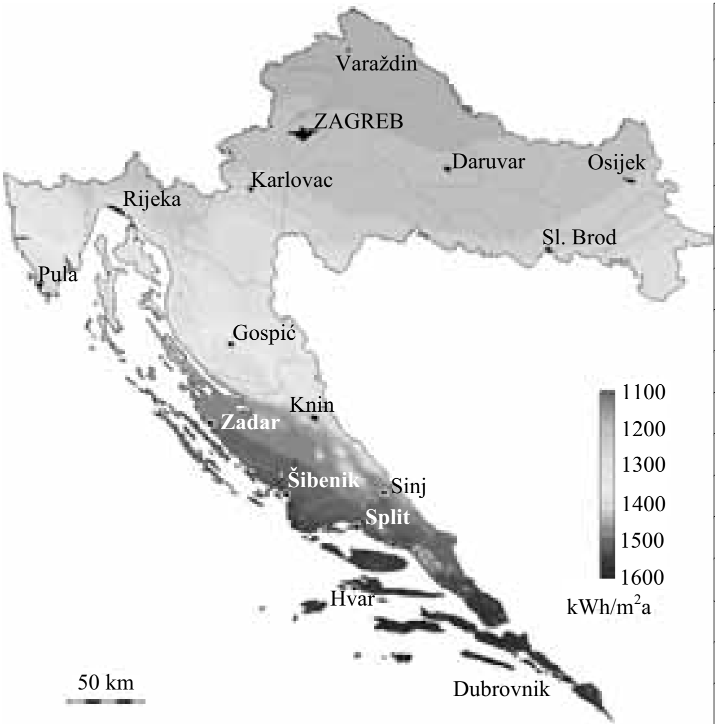


Fig. 1. Monthly-based and test reference year space heating and cooling energy demands for Rijeka.

The monthly-based calculations match quite well with the ones from the test reference year. The monthly-based space heating and cooling energy demands are 9.92 and 9.83 kWh/m^{2}a, respectively. The test reference year hourly-based space heating and cooling energy demands are 10.27 and 9.74 kWh/m^{2}a.

2.2. Space heating and cooling energy demands

Taking into account that both space heating and cooling energy demand have to be lower than 15 kWh/m^{2}a and that the peak heating load should be below 10 W/m^2 all year round, the minimum necessary thickness of thermal insulation and south-oriented window area for passive house standards are determined for the locations shown in Fig. 2.



Location	Heating degree-days, HDD_{12}	Design ambient temperature, °C
Daruvar	2950	-10
Dubrovnik	1190	0
Gospić	3500	-14.2
Hvar	1180	0.5
Karlovac	2960	-10
Knin	2310	-6.2
Osijek	3010	-13.3
Pula	2030	-2.7
Rijeka	2045	-3.9
Sinj	2395	-5.5
Sl. Brod	3050	-13.3
Split	1440	-1.7
Šibenik	1630	-2.3
Varaždin	3180	-13.8
Zadar	1685	-3
Zagreb	2730	-9.9

Fig. 2. Solar irradiation on horizontal plane, heating degree-days and design ambient temperature for chosen locations in Croatia. Solar irradiation map from [5]

Although space heating and cooling energy demands depend on numerous factors, thermal insulation thickness and window area have major impact on these values. Calculations were performed with the aim of reaching passive house standards with minimum necessary insulation thickness and area of south-oriented windows: the results are given in Fig. 3. With respect to the climate, the chosen locations may be divided in three groups: locations with mediterranean climate (Adriatic coast and islands), locations with continental climate and locations with mountainous climate (Gospić). The design ambient temperature determines the necessary thickness of thermal insulation to limit the peak heating load to 10 W/m^2: passive house standards are met with 21 cm (Hvar) to 35 cm (Knin) of thermal insulation in coastal regions and islands. Passive houses in locations with continental climate require from 44 cm (Zagreb) to 59 cm (Sl. Brod) of thermal insulation. The City of Gospić, characterized by 3500 heating degree-days and design ambient temperature of -14 °C, presents extreme winter conditions in Croatia and the appropriate passive house should have thermal insulation thick as 60 cm. The south-oriented window area was selected in the way to result with a minimum total space energy demand (heating+cooling) in the passive house. Space cooling energy demands were estimated from solar gains through windows and for no special shading or summer ventilation strategy except the abovementioned roof overhang. The window area assumes very different values throughout Croatia: from only 5 m^2 in southernmost regions to 15-19 m^2 in northern continental and mountain regions. The selected thermal insulation thickness and south-oriented window area result in space heating energy demands that range from 10 kWh/m^{2}a for passive houses in coastal regions and islands to 14-15 kwh/m^{2}a for passive houses in continental and mountain regions. The resulting space cooling energy demands range from 6 kWh/m^{2}a in Gospić to 14 kWh/m^{2}a in southernmost locations of Croatia (Dubrovnik, Split and Hvar) and in few locations in the continental region (Osijek and Karlovac).

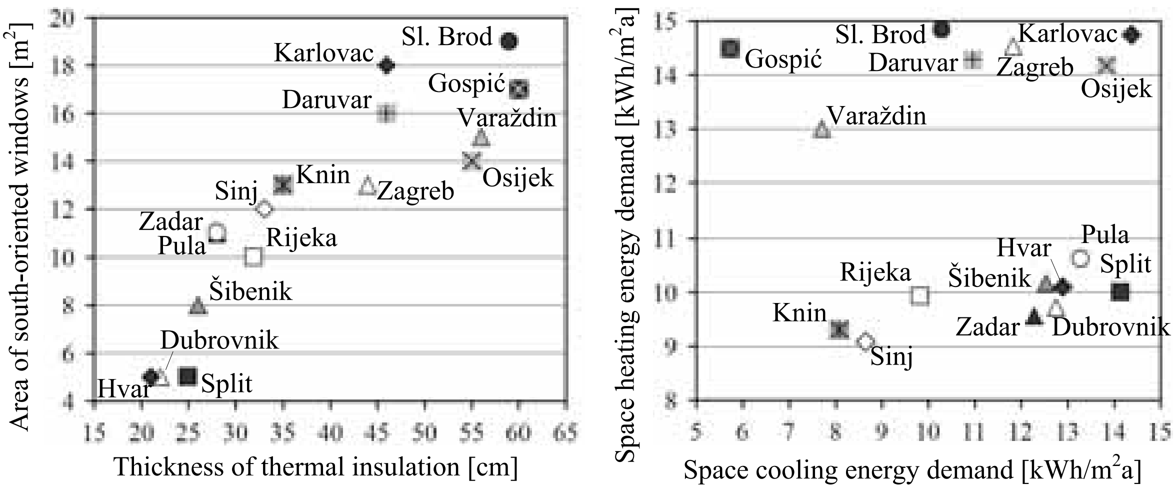


Fig. 3. Thickness of thermal insulation and area of south-oriented windows (left) and space heating and cooling energy demands (right) for passive houses in selected locations in Croatia

3. Passive house energy systems

3.1. Solar collectors and PV cells

According passive house standards the maximum annual energy demand for space heating, domestic hot water (DHW) and household appliances may not exceed 42 kWh/m^{2}a. Systems for the conversion of solar energy into heating energy and electricity are common for passive houses in location with considerable amounts of solar irradiation like in Croatia. The necessary solar collector area was estimated to cover 90% of the annual DHW heating energy demands. The annual DHW heating demand of 21.2 kWh/m^{2}a results from the passive house standard consumption of 25 litres of hot water a day per occupant at Δt = 50°C. Flat plate collectors with conversion factor of 0.82 and heat loss coefficient of 2.15 W/m^{2}K are considered. The collectors are roof-mounted and south-oriented with tilt angle of 45°. Because of limited space in the DHW storage tank, only a fraction of the available solar irradiation can be converted into usable heating energy. The usable solar irradiation fraction is the ratio between the converted solar irradiation and the available solar irradiation. This fraction is higher in winter period and lower during summer months: to produce realistic estimations the usable solar irradiation fraction is supposed to be 0.6 from October to March and 0.3 from April to September in all calculations. These values are rather conservative and result in an average annual usable solar irradiation fraction of about 0.4. In the same way as for the solar collectors, the necessary PV cell area was estimated in order to supply 90% of the household appliances electricity demands. The annual electricity demand is supposed to be 30 kWh/m^{2}a. The PV system solar energy conversion efficiency is 10% and the cells are south-oriented with tilt angle of 45°. The usable solar irradiation fraction of 0.4 throughout the whole year takes into account the asynchrony between demands and PV system electricity production. The excess electricity is then delivered to the local grid or stored in batteries.

The necessary solar collector and PV cell area for 90% coverage of DHW heating and electricity demands for passive houses in the chosen locations are given in Fig. 4. About 5 m^2 of solar collectors may cover up to 90% of the DHW heating energy demands in passive houses in coastal regions and islands. The solar collector area should be increased to 6-7 m^2 to achieve same coverage fractions in passive houses located in continental regions. A PV cell area of about 50 m^2 could cover 90% of annual electricity demands in passive houses along the Adriatic coast. However, to supply same electricity fractions in continental regions the PV cell area should be almost doubled.

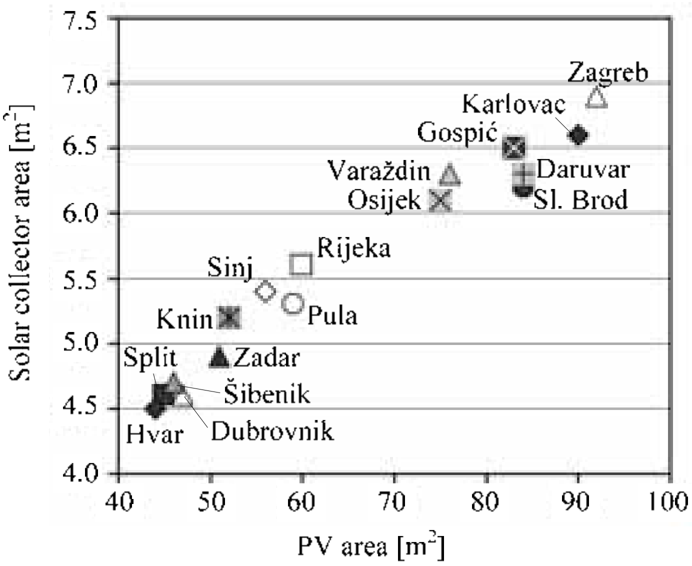


Fig. 4. Necessary solar collector and PV cell area for 90% coverage of DHW heating and household appliances electricity demand for chosen locations in Croatia

3.2. Solar collectors and heat pump for passive house heating and cooling

Calculations based on average monthly ambient air temperature and solar irradiation data may produce good estimations, but calculations with hourly-step data are more sophisticated and more time-consuming, though. The test reference year for the City of Rijeka was incorporated in calculations to analyse the efficiency of a solar combisystem made of solar collectors and ambient air-to-water heat pump connected in mixed mode.

Profiles of space heating, cooling and DHW energy demands for the passive house in Rijeka are shown in Fig. 5. The DHW consumption profile was generated using *DHWcalc* software [6].

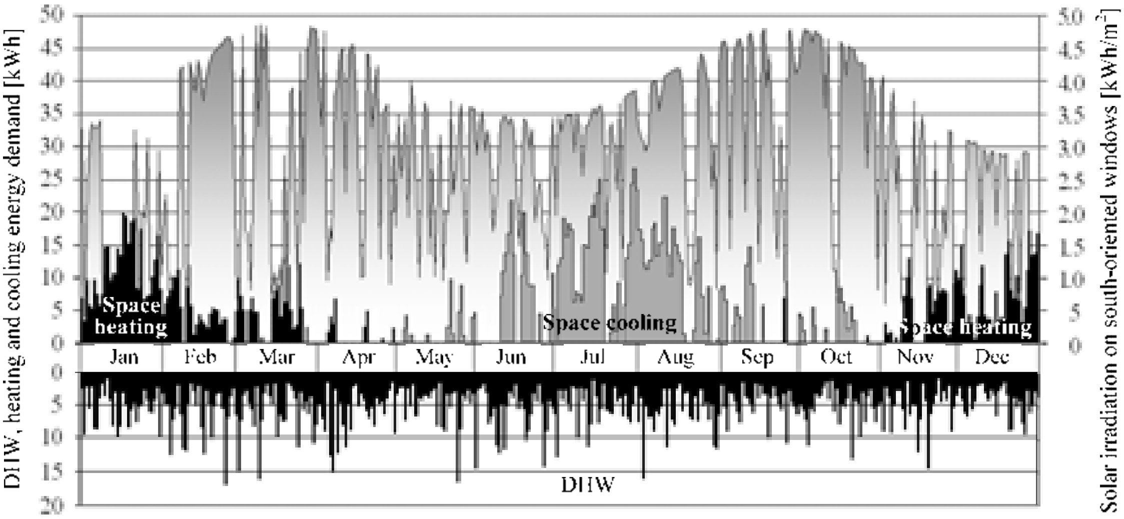


Fig. 5. Daily profiles of passive house energy demands for DHW preparation, space heating and cooling. Solar irradiation per m^2 of south-oriented windows in Rijeka.

The solar combisystem shown in Fig. 6. supplies space heating and DHW energy as well as space cooling energy. Space heating and cooling energy are supplied via the passive house ventilation system. DHW is heated instantaneously through two immersed finned-tube heat exchangers in the heat storage tank. In summer period, the heat pump switches to cooling mode and solar collectors are responsible for all DHW heating energy demands. The average seasonal heat pump COP for heating mode is 2.65 (HSPF = 9) and for cooling mode 3.42 (SEER = 13). Similar solar combisystems having gas, pellet or wood boiler as an auxiliary heating energy source are common in west-European countries and have been thoroughly investigated in [7].

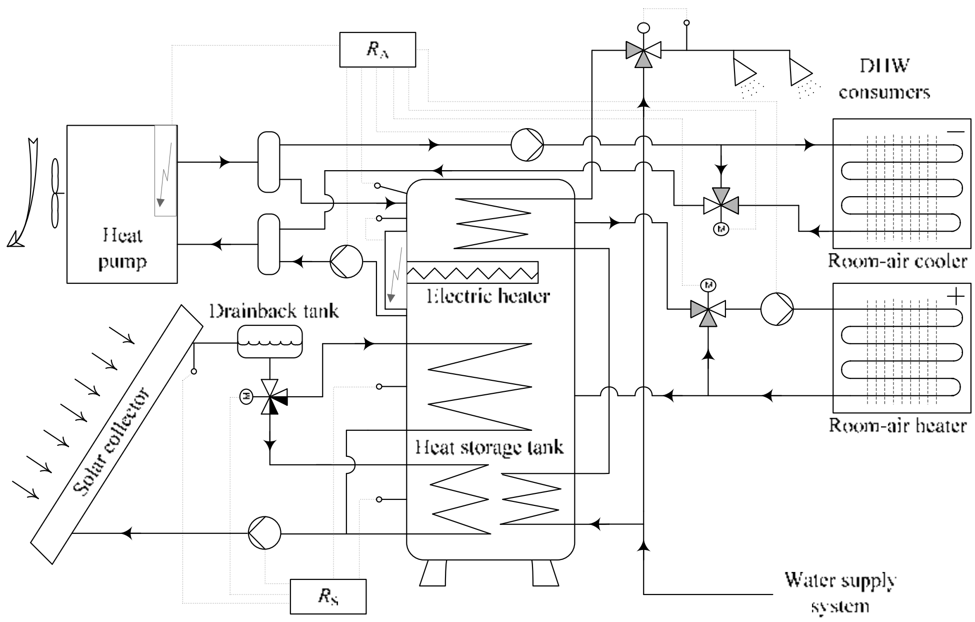


Fig. 6. Hydraulic scheme of the passive house solar combisystem

The solar combisystem performance has been characterized with three non-dimensional numbers:

- the heating coverage fraction, f_{cov}
- the primary energy saving fraction, f_{sav} and
- the usable solar irradiation fraction, f_{sun}

The solar combisystem heating coverage fraction is the share of supplied solar energy in passive house heating energy demands (space heating, DHW and system heat losses). The primary energy saving fraction is the ratio between primary energy consumption in the solar combisystem and primary energy consumption in a reference non-solar heating-cooling system. The reference non-solar heating-cooling system has a gas boiler with average annual energy efficiency of 85% and a split AC unit with average cooling mode COP of 3.42 for space cooling. The usable solar irradiation fraction is the ratio between the used solar irradiation and the available solar irradiation to solar collectors. These fractions are plotted in dependence of the solar combisystem heat storage volume and solar collector area and shown in fig. 7. Solar collectors are south-oriented with tilt angle of 60°.

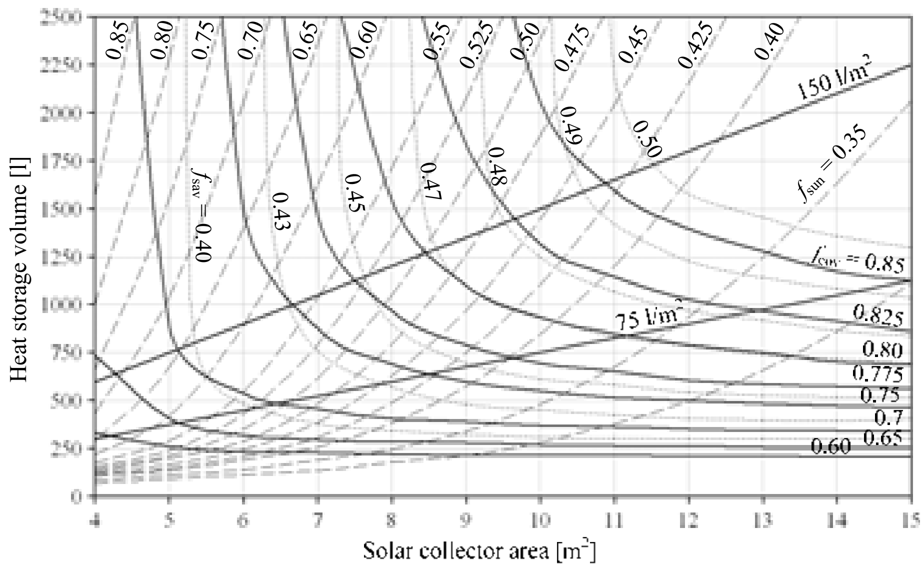


Fig. 7. Heating coverage, primary energy saving and usable solar irradiation fraction in dependence of solar combisystem heat storage volume and solar collector area

A solar combisystem with heat storage tank of 1000 litres, 9 m^2 of solar collectors and a small ambient air-to-water heat pump (about 1.5 kW_{el}) saves 46.6% of the primary energy consumed in the reference non-solar heating-cooling system. Solar energy provides about 80% of the annual heating energy demands. The solar collectors converts about 45% of the total available solar energy into usable heating energy. However, capital investments in this kind of solar combisystems are still the main drawback: it was estimated that the capital investment in the reference non-solar heating-cooling system is half of the investment in the solar collector-heat pump system. Nevertheless, lower energy consumptions during the solar combisystem lifetime can reduce the overall additional costs to about 50%, compared to the reference heating-cooling system.

Annual primary energy consumptions in the selected solar combisystem and in the reference non-solar system are listed in Table 1.

Table 1.: Primary energy consumptions in heating-cooling systems for a passive house in Rijeka

Passive house energy demands [kWh/m^{2}a]			**Heating-cooling system demands [kWh/m^{2}a]**	
Space heating	Space cooling	DHW	Heat losses	Parasitic electricity
10.27	9.74	21.2	4.96[1)] / 8.67[2)]	7.14[1)] / 8.32[2)]
[1)]Non-solar reference system annual primary energy consumption [kWh/m^{2}a]				
12.08	7.79	24.94	5.84	17.85
[2)]Solar combisystem annual primary energy consumption [kWh/m^{2}a]				
5.53	7.79	1.69	0.76	20.80

4. Conclusion

To this day, Germany, Austria, Scandinavian countries and United States have built a total of 20 000 passive houses. Croatia, with more favourable climatic conditions, has only a few. Passive house standards can be reached with 20 to 35 cm thick thermal insulation in locations along the Adriatic coast. Thermal insulation should be thickened to about 45 to 60 cm for passive houses in continental and mountainous regions of Croatia. Due to large amounts of solar irradiation, the passive houses in the Croatian south-Adriatic region should be designed with caution in order to prevent room overheating. On the other hand, passive houses in continental regions should have window areas as large as 15 to 20 m^2. Solar energy conversion systems of modest sizes could provide most of the space and DHW heating energy and electricity for passive houses in the south-Adriatic region. However, the sizes of these systems should be doubled if equal effects are to be achieved in northernmost continental and mountainous regions of Croatia. Further, the performance of a combisystem for passive house in Rijeka was analyzed: 9 m^2 of solar collectors, 1000 litres of heat storage and a small ambient air-to-water heat pump could cover 80% of the total annual heating energy demands and save 47% of the primary energy consumed in a non-solar heating-cooling system. This combisystem would perform even better for passive houses in the south-Adriatic region. Passive houses employing active and passive solar energy solutions are expected to become very common in the time to come in Croatia.

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