Optimal integration of solar assisted heating systems in residential buildings

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Abstract- The decrease in conventional energy resources, environmental pollution issues and climate change are the leading factors inducing the increase of energy efficiency criteria. Trends to improve energy efficiency are mainly aimed at the construction sector as one of the leading sectors in energy consumption. In the paper are analyzed the performance of the decentralized solar assisted heating systems (SAHS) for climatic conditions in Macedonia in order to assess the possibility to be integrated as part of the district heating system. The analysis is based on a holistic approach, in which the performance of the SAHS is generally functionally dependent on four factors: (1) the characteristics of each component, (2) the system structure and mutual interactions of the components, (3) the management method and (4) specific energy consumption for heating of the building. The specific analysis is directed toward assessment of the solar fraction of the SAHS as a function of the building energy performance and system heating temperature range. The numerical modeling of the processes occurring in systems is performed with the dynamic simulation software TRNSYS. It is developed dynamic model of the solar bivalent system and reference building. The dynamic model contributes to the flexibility of conducting parametric analysis. The obtained results from the parametric analysis are condensed in a general table upon which analysis of system performance was performed.

Index Terms- Solar energy, solar collector, heating, simulation

I. INTRODUCTION

It is well known that in the European Union more than 25% of the total energy consumption is due to building sector, where heating and cooling energy has the major share in the total energy consumption. Energy efficiency across the energy value chain (from primary energy through produced and final energy to delivered and useful energy) acts as an enabler for the integration of higher shares of renewable (and waste heat) sources. As such, the European Commission sees energy efficiency as a key element to reduce GHG emissions, foster European competitiveness, and ensure a secure energy supply. This has been translated into the 2030 objectives of the Energy Union, notably reducing Europe's energy use by 32.5% compared to the business as usual projections, which will significantly contribute to cutting GHG emissions by at least 40% below 1990 levels [1].

Flat-plate solar collectors have potential applications in HVAC systems, industrial thermal processes, and solar engineering. They are the most economical and popular in solar domestic heating water system since they are permanently fixed in positions, have simple construction, and require little maintenance. The design of a solar energy system is generally concerned with obtaining maximum efficiency at minimum cost.
Solar thermal systems for hot water production are already mandatory in new buildings according to solar ordinances for example in Spain [2], Portugal, Italy, Greece and other European countries [3].

Systems combining production of domestic hot water (DHW) and space heating systems are well suited to middle and high latitudes, due to significantly higher solar radiation in the transitional period around winter (September-October and March-May) and the significant heating demand in these latitudes at that time [4].

Installations with large solar collector areas and small size heat storage capacity can cover around 50% of the total heat demand. This percentage can be higher in some cases of large storage capacities and primary energy savings up to 80% [5]. Simulations of central solar heating plants with seasonal storage (CSHPSS) have shown that the solar fraction of such systems varies between 50% and 100% [6, 7]. The heat produced by the collectors may be stored in thermal energy storages in order to provide domestic hot water and space heating when required [8].

II. BACKGROUND ANALYSIS

According the IEA (International Energy Agency) building sector represents 32% of the total final energy consumption and converted in terms of primary energy this will be around 40%. Inspected deeper, the heating energy consumption represents over 60% of the total energy demand in the building. Space heating and hot water heating account for over 75% of the energy used in single and multi-family homes [9]. Solar technologies can supply the energy for all the building's needs—heating, cooling, hot water, light and electricity—without the harmful effects of greenhouse gas emissions created by fossil fuels. Usually, the maximum demand for cooling coincides with the maximum availability of solar radiation, whereas conventional electrical-compressor chillers have the problem of providing their required capacity in the hottest hours.
A solar system can be designed to satisfy any particular space and water heating application. Technically considered, it is

feasible to design a system which can satisfy 100% of the heating needs of a building, but generally it is economically not profitable solution. In practice solar heating systems are designed to displace up to about 50% of conventional fuel needs and require auxiliary heating systems that are fully capable of supplying the total heating load when no solar energy is being collected and when solar energy has been depleted.

A 100% renewable energy district makes optimal use of locally available renewable energy sources and waste heat. For historical reasons, cities and towns developed along rivers, lakes and seashores which provide access to environmental heat. All these sources make high and low-temperature renewable energy available, and their usage is highly replicable because it is accessible right where it is needed. In order to use local sources, municipalities, energy utilities and the industry have to collaborate across sectors.

The energy landscape is shaped by cities. 72% of the European population (EU28) lives in urban areas – defined as cities, towns and suburbs. Globally, cities account for about two-thirds of primary energy demand and 70% of total energy-related carbon dioxide (CO2) emissions. The energy and carbon footprint of urban areas will increase with urbanization and the growing economic activity of urban citizens. The decarbonization of cities and city districts presents an imperative and an obvious area of priority. Districts, in particular, have specific opportunities to drive the decarbonization efforts as they know best about their local needs and locally available infrastructure and resources [10].

Regarding multi apartment buildings it is recommended, either all apartments to be connected to the district heating network or all to have individual heating system. Observed from a broader perspective, heating in large urban areas should be organized and controlled i.e. centralized, but under economically acceptable conditions for the users, aiming to protect the environment [11].

III. METHODOLOGY DEVELOPEMENT

The development of solar simulation capabilities greatly assists in the promotion of practical solar systems. Simulations, like any other calculations are only as good as the models that are the basis of the program and the skill which they are used. Some of the programs that have been applied to solar processes have been written specifically for study of solar energy systems. Other were intended for non-solar applications but have had models of solar components added to them to make them useful for solar problems.

The method for the modeling is separated into three distinct stages: stage 1 building modeling, stage 2 system plant modeling stage, and stage 3 - manual calculations.

To describe the contribution of a solar part of the bivalent heating system and to make an adequate comparison with the results of the detailed simulation models, it is necessary to point out that the results of the comparisons depend on:

- Selected reference conditions related to the required energy, energy sources, parameter setting and standard components
- The output value of the leading function for the annual simulation of the considered system which serves to evaluate the performance of the bivalent system (example fuel savings in the bivalent system with solar energy compared to the reference system without solar energy)
- Mathematical accuracy of system simulations and selection of identical simulation models and system components

The results of the comparison are in correlation with the selected reference conditions, such as the energy consumption, type of energy source, initially set values of the parameters, type of standard components used as well as output values of the leading function which compares the results of the annual system simulation on which basis the performance of the bivalent system is evaluated.

Current versions of TRNSYS have in executive program convergence promoters and other means of speeding computations. There are three integration algorithms in TRNSYS, the user can choose the one best suited to the problem at a hand. The one that is extensively used is the modified Euler method. It is essentially a first order predictor corrector algorithm using Euler's method for the predicting step and the trapezoid rule for the correction step.

As an additional component library (also used in this work) is the developed by the company Thermal Energy System Specialist (TESS). The TESS Applications Library is an assortment of scheduling and setpoint applications that use the TRNSYS Simulation Studio plugin feature [12]. These components are extremely useful for creating daily, weekly, monthly schedules, normalized occupancy, lighting, or equipment schedules, and setpoints for thermostats.

A. Modeling of the solar assisted heating system

The operation of most solar energy systems is inherently transient considering the dynamic nature of the heat transfer processes. There is no such thing as steady-state operation when one considers the transient nature of the driving forces like the solar energy caused by the stochastic nature of the sun radiation.

For the flat plate solar collector it is used the Type 539 from the TESS library. This model is selected because compared to Type 1 from the TRNSYS library it takes into consideration the influence of the capacitance effect to the temperature change.

In the analyzed system for the storage tanks is used the Type 60c from the TRNSYS library which represents a stratified fluid storage tank with internal heaters and internal heat exchangers. Water tank may operate with significant degrees of stratification, that is with the top of the tank hotter than the bottom. The used tank component it is modeled by assuming that the tank consists of N ($N \leq 100$) fully-mixed equal volume segments.

In the simulation for the additional heating of the fluid entering the building heating system it is used model of proportionally controlled fluid heater. As a control external proportional control (an input signal between 0 and 1) is used which is in effect as long as a fluid set point temperature is not exceeded. So, if the set point is exceeded, the proportional control is internally modified to limit the fluid outlet temperature

The used differential controller in the simulations is the component Type 2 from the TRNSYS library. This controller generates a control function γ_0 that can have values of 0 or 1. The value of γ_0 is chosen as a function of the difference between upper and lower temperatures, TH and TL, compared with two dead band temperature differences, ΔT_H and ΔT_L. The new value of γ_0 is dependent on whether γ_i = 0 or 1. The controller is normally used with γ_0 connected to γ_i giving a hysteresis effect. For safety considerations, a high limit cut-out is included with the TYPE 2 controller. Regardless of the dead band conditions, the control function will be set to zero if the high limit condition is exceeded.

For the building simulation is used the Type 56 from the TRNSYS library. Type 56 describes a building with multiple thermal zones, i.e. rooms. The model uses data from wall and window materials and thicknesses. Each room has a homogenous temperature, and radiation heat between the rooms is based on the room area. Heat addition from solar direct and diffuse radiation is calculated for each room depending on window and heat transfer properties. Type 56 models the thermal behavior of a building divided into different thermal zones. In order to use this type, a separate pre-processing program must first be executed. The TRNBuild program reads in and processes a file containing the building description and generates two files (described later) that will be used by the TYPE 56 component during a TRNSYS simulation.

In the simulations for the solar radiation data was used the weather component from the TRNSYS library the Type 15 which supplies input data in the solar collector numerical model: ambient temperature, beam, sky and diffuse radiation for the tilted surface (calculated regarding the tilt angle of the collector), solar zenith and solar azimuth angle. The weather data in this model are generated in a so-called referent year which contains data based on stochastic methods, interpolations where the data for temperatures, wind speed are for the period between 1961 – 2009, while for the sun radiation are for the period 1985 – 2005. In determining this kind of reference year, the typical range of meteorological measurements at hourly intervals are required for a period of several years, a process which results in a complete picture of the climatic conditions that govern the examined area. But this does not mean simply determining the average of all years, because it does not adequately predict the changes that may occur, but is selected representative month for this area. The procedure is as follows: for each month is determined average solar radiation over the entire period of measurement and individual monthly average radiation for each year within the period considered. Monthly value to the average radiation closest or equal to the global monthly average over the period of measurement is chosen as a representative month for typical reference year. This process is repeated for each month of the year where then the selected months are grouped and an hourly average values over the year are provided.

Assessment of thermal performance of the solar assisted heating system is performed through a dynamic simulation model with transient behavior implemented via thermal and mass storage terms as well as delay times. The model scheme is presented on the Figure 1.

The analyzed system generally consists of four main subsystems:

1. First subsystem composed of solar collectors with complete hydraulic fittings and control - differential controllers, plate heat exchangers i.e. this system is represented the source of thermal energy for heating
2. Second is the subsystem for thermal storage which includes the storage tanks for hot water that actually represents the connection between the heating systems in the building
3. The heating system introduced with heating devices, hydraulic armature heat exchangers and conventional sources of heat represented by the district heat
4. The fourth subsystem is the consumer of thermal energy i.e. the building. This system is represented by the thermal characteristics of the object its orientation in space.

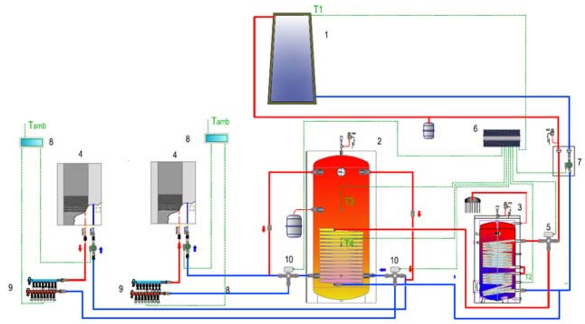

Figure 1. Scheme of the analysed solar assisted heating system

The working fluid from the solar collectors indirectly through heat exchangers is used to heat the domestic hot water or heat the fluid in the storage tank, further used as part of the heating energy in the building. The circulation of the solar collectors working fluid for the storage tanks is provided by circulating pump, controlled by a differential controller. First condition for the pump to be switched on is the temperature difference between the collector outlet temperature and the fluid temperature in storage tank to be greater than the set upper dead band. The control logic for switching between the two tanks is solved using the two controllers Type 2b (K1 and K2, which on the scheme on Figure 1 are represented with a common controller marked with 6) one flow diverter Type 11f (on Figure 1 marked as 5). The advantage has the controller K2 of the tank 2 i.e. the initial input control signal (on/off) for the controller of the DHW tank K1 is received from the controller K2 i.e. when the controller K2 is on, then the controller K1 is off.

The collector(s) thermal efficiency in the simulation is determined using the equation component from the TRNSYS library. The equation considers ratio between the useful energy gain from all of the collectors transferred to the fluid and the total tilted radiation for the collector surface. The data for the quantity of useful energy gain and total radiation in the equation is read from the quantity integrator which integrates these values in the predefined period defined from the required value period thermal efficiency and energy i.e. daily, weekly, monthly, and yearly or any other time interval.

Also in order to calculate the different performance indicators, some necessary values are defined: the useful solar energy (E_{SU}), the parasitic electricity demand of the whole system (E_{aux}) and of the solar part ($E_{aux\ sol}$), the thermal losses of the hot and cold storage ($Q_{loss\ HS}$ and $Q_{loss\ CS}$), the thermal losses of the hot storage due to the heating backup system ($Q_{loss\ HB}$), the thermal losses of

the cold storage due to the cooling backup system ($Q_{loss\ CB}$), the final energy consumption of the heating backup system ($Cons_{HB}$) and of the cooling backup system ($Cons_{CB}$).
The building has one floor with a total conditioned area of 150 m^2. In Table 1 are presented data for: surfaces and orientation of exterior walls, windows, floor, roof and coefficients of heat transfer.

Table 1. Reference building characteristics and thermal performance data

Surface	Orientation	Area, m²	Building I	Building II	Building III
			U value, W/m²K		
Out.wall 1	North	42	0.58	0.33	0.18
Windows 1	North	3	1.40	1.40	1.40
Out.wall 2	East	25.5	0.58	0.33	0.18
Windows 2	East	4.5	1.40	1.40	1.40
Out.wall 3	West	25.5	0.58	0.33	0.18
Windows 3	West	4.5	1.40	1.40	1.40
Out.wall 4	South	42	0.58	0.33	0.18
Windows 4	South	3	1.40	1.40	1.40
Floor	-	150	0.33	0.33	0.24
Roof	-	150	0.54	0.42	0.35
Window type	Double glazed TRNSYS library (w4-lib data)				
Windows solar heat gain coefficient;g-value	0.589				
Out.wall construction	2 x Plaster 2cm, brick 25cm		Insulation 5 cm	Insulation 10 cm	Insulation 20 cm
Floor	Granite tile 6cm, cement mortar 5cm , concrete slab 20cm		Insulation 10 cm	Insulation 10 cm	Insulation 15 cm
Roof	Concrete slab 20cm, hydro isolation, cement mortar 5cm		Insulation 15 cm	Insulation 20 cm	Insulation 25 cm
Outside convective heat transfer coefficient	α_{out} = 25 W/m²K				
Inside convective heat transfer coefficient	α_{in} = 7,7 W/m²K				

The calculation of energy consumption in the building is obtained directly as output size of the numerical model of the object in kJ/h value which further is integrated for the required period with the quantity integrator. Monthly analysis is performed for the building heat energy consumption regarding different heat transfer coefficients i.e. different wall, floor and roof isolation thickness thus defining three types of Building energy performances I, II and III, as presented in Table 1. Simulation results are graphically presented on Figure 2:

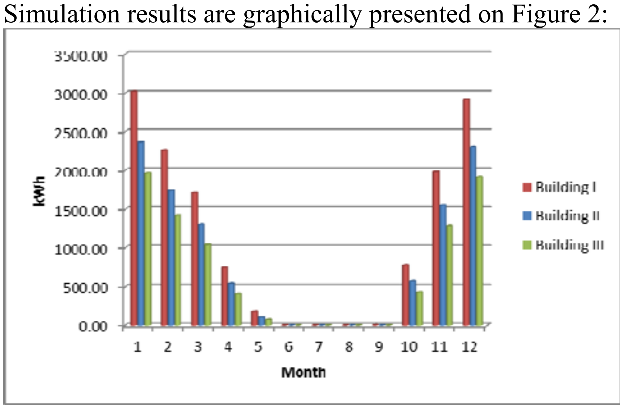

Figure 2. Monthly heating energy consumption for the reference Building for three energy performance indicators

Analyzing the presented simulation results on Figure 2 can be noticed that as expected the Building III has the smallest heat consumption i.e. regarding specific annual energy consumption, Building I has annual heat consumption of 13500 kWh or specific 90 kWh/m^{2}a, Building II has 10500kWh or specific heat consumption 70 kWh/m^{2}a and Building III has energy consumption of 8550 kWh or specific energy 57 kWh/m^{2}a. Comparing the energy consumption it can be noticed that Building III has 42% lower than Building I and 19% than Building II.

Besides the analysis of the primary parameter solar fraction, the influence of the heating system type is analyzed the influence of the heating system type regarding the heat transfer elements (underfloor heating or radiators) and efficiency of solar collectors, solar fraction and the total consumption of heating energy. In the first case analyzed, radiators are set as heating elements.

In this case as parametric variables are considered: heating system type (radiator and underfloor), specific building heat energy consumption defined with three building types differencing only in thermal insulation, collector type, collector area and storage tank volume. Solar fractions are in the range from 8% for radiator heating system, building type I i.e. specific heat consumption of 70 kWh/m^2 a, 16 m^2 collector area, storage tank 1000 l-radiator heating up to 52% solar fraction for underfloor heating system, building type III i.e. specific heat consumption of 57 kWh/m^2 a for 64 m^2 collector area, storage tank 2000 l. This fraction of the heater power is supplied as internal radiative gains and distributed to the walls of the zone. As the set temperature for the heating equipment is related to the air temperature of the zone, the radiative fraction of the heating power RRAD cannot be higher than 0.99 in order to have a convective part remaining to ensure stable control of the heating equipment. The radiators are modeled with Type 1231 from the Tess Library. The heating radiator model is based on the ASHRAE method outlined in the 2004 ASHRAE Handbook - HVAC Systems and Equipment.

The fluid in the storage tank indirectly is heated by solar collectors which further with the circulating pump mass flow rate of 2000 kg/h is transferred through the auxiliary heater to the underfloor heating. The auxiliary heater is considered that is heat exchanger with the primary side connected to the District Heating network, nominal thermal power of 12kW. The output working fluid temperature from the auxiliary heating is set to me maintained on 50° C if case when heat transfer elements are radiators while for the underfloor heating is set to 40 °C. The system considers heating DHW tank with a daily hot water consumption of 200 l with internal heat exchanger and an external auxiliary heating with installed power of 9 kW. The volume of the storage tank is considered as a parameter in the analysis with values of 1000 l, 1500 and 2000 l. Each of these storage tanks are modeled with an internal heat exchanger which technical characteristics as given in Annex 1. Auxiliary heater power is 12 kW.

Return i.e. exit temperature of the fluid from the heating system is a dynamic variable that depends on several parameters, the parameter value is output from the numerical model of radiators and floor heating. If the return temperature of the working fluid is higher than the temperature in the storage tank measured at the highest point and redirect directly to the auxiliary heater.

The domestic hot water tank, differential controller upper band is set to five, lower dead band to two, while for the storage tank both values are three.

The mass flow rate through the solar collectors is selected to be 50 kg/h m^2 i.e. for the 16 m^2 is 800 kg/h, for 32 m^2 is 1600 kg/h and for 64 m^2 is 3200 kg/h.

The simulations are done with time step of 7.5 min and the result were integrated on monthly basis. Presented results are averaged values from the monthly values and the period of analysis are the heating season months for Skopje i.e. October – April. On the Figure 3 are presented the simulation results, values for the solar fraction as a function from: heating distribution system type (radiator-high temperature, underfloor heating=low temperature), installed solar collector area and storage tank volume.

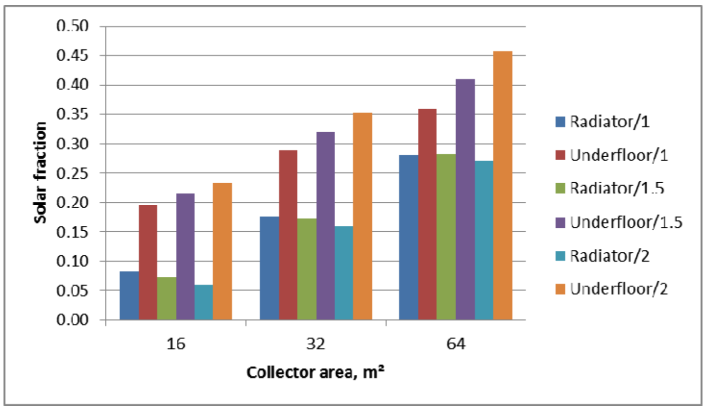

Figure 3. Solar fraction for Building I, radiator and underfloor heating as function from collector array area and storage volume

The number that is written in the series name in the diagram after radiator and underfloor, indicates the storage tank volume in m^3. It's easily noticeable on the results from Figure 3 that there are differences between the solar fractions i.e. higher differences are occurring for the combination of lower solar collector areas and bigger storage volumes. This is because first the analyzed Building I has highest heat energy consumption which results in high frequency heat energy discharge from the storage tank. The underfloor heating has bigger solar fraction since it uses the thermal mass of the floor which buffers the temperature fluctuations in the building i.e. tank discharge frequencies thus allowing more time the tank to be reheated with solar energy and the second important influencing factor is that the underfloor heating has 10°C lower design driving temperature compared to radiator system which has positive influence on the collector efficiency.

Another possible analysis is to gain insight for the influence of the specific building energy consumption on the solar fraction. On Figure 4 are presented results from this analysis where it is obvious that underfloor heating has bigger solar fractions ranging from 24% up to 73%. This solar fraction differences trend between radiator and underfloor solar assisted heating increases if the building lowers the specific heat energy consumption and lowers the collector area. This analysis is done for constant volume of storage tank, 1500l and internal heat exchanger.

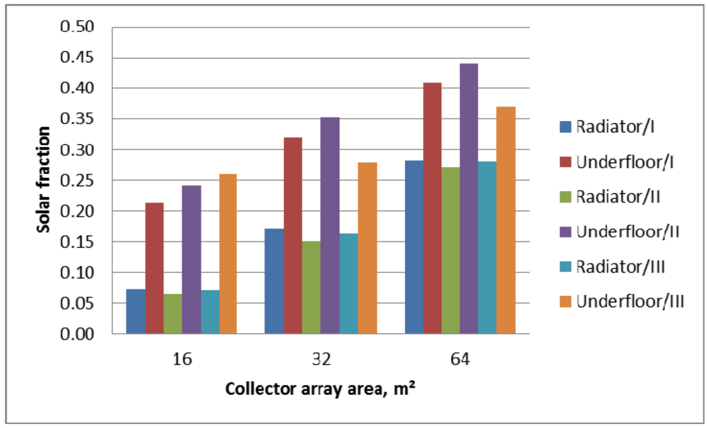

Figure 4. Solar fraction for heating with storage tank 1500l regard of collector array area building type

According to the presented results on Figure 4, can be concluded that higher discrepancies for solar fractions regarding heating system type (radiator vs. underfloor heating) are noticeable for the building with higher heating energy consumption – lower energy performance. This is result since building with higher heat losses has higher energy consumption causing frequent discharge of the storage energy thus lower average storage temperature and increased

IV. CONCLUSION

The size of a solar system (primarily the storage volume and collector area) for a particular building depends on the portion of the total load of the system is expected to provide. Size is also strongly dependent on the climate and location. The main aim of this paper was to obtain indicators for the range of energy contribution (solar fraction) from the solar thermal systems in the heating energy for the residential sector for climate conditions in R.Macedonia. This data – the solar fraction and the amount of auxiliary energy could serve as an indicator in the analyses for determining the feasibility for the integration a decentralized solar thermal systems into buildings as part of a district heating system.

First analysis was performed to examine the influence of the heating system type (radiator and underfloor heating) to the system thermal performance i.e. to the solar fraction, collector efficiency and "real" efficiency. In the analysis also were considered different: collector areas (16 m^2, 32 m^2 and 64 m^2), storage tank volumes (1000 l, 1500l, 2000 l) and three types of buildings (I, II, III) with different specific heat consumptions 90 kWh/m^2 a, 70 kWh/m^2 and 57 kWh/m^2 a respectively. Results from the simulation showed that for building type I i.e. specific heat consumption of 90 kWh/m^2a, 16 m^2 collector area, storage tank 1000 l and radiator heating solar energy can cover 8% from the annual heat energy needs while the maximum solar fraction of 52% is achieved for Building III (57 kWh/m^2a) with underfloor heating system 64 m^2 collector area and 2000l storage tank. With 0,1 $m^2/m^2_{conditioned}$ specific collector area per conditioned surface can be achieved between 20 – 25 % solar fraction, with 0,2 $m^2/m^2_{conditioned}$ range round 35% , and with 0,4 $m^2/m^2_{conditioned}$ maximum 50 %. It should be noted that the solar fraction also strongly depends from the storage tank volume and for the radiator heating system increasing the storage volume results in decrease of solar fraction while at the underfloor heating its vice versa. It is recommended the storage volume to be in the range 50-60 l/m^2 collector area in order to optimize between the solar fraction and collector efficiency. As a summary can be concluded that there is potential for integration of solar thermal systems into heating systems in buildings (for climate conditions in Macedonia), but the initial prerequisite is to have higher class of energy efficient buildings (with specific annual energy consumption of 50 kWh/m^2 or less) with a low temperature heating system. However, it is necessary to make another series of analysis considering energy prices, technical feasibility on field etc.

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