Optimization of a Building Integrated Solar Thermal System with Seasonal Storage

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ABSTRACT

In the current work a Building Integrated Solar Thermal System with Seasonal Storage is optimized with the use of TRNSYS modelling software in order to evaluate different options of integration of the solar collectors. The model calculates the space heating and domestic hot water needs of a typical single-family detached home in the city of Thessaloniki, Greece that has been built according to the latest building code. The contribution of the solar system, as well as the thermal load covered by the auxiliary conventional system is determined and the seasonal solar fraction is calculated. A parametric analysis on the impact of various solar collector areas and types, building integration type, as well as the volume of STES is also presented in order to optimize system design and obtain a seasonal combined solar fraction of at least 40%.

1. Introduction

The building sector represents one of the biggest energy consumers in the European Union (EU), accounting for more than 40% of final energy consumption (European Environment Agency, 2010). To combat that, the EU implemented a series of directives that promote the use of energy alternatives for buildings, used primarily for electricity, heating, cooling and the provision of hot water, that led to Directive 2010/31/EC (European Commission, 2010) which defined minimum rules on the performance of buildings and introduced energy certificates, taking into account the external climatic conditions and defining the Net Zero Energy Building (NZEB). These actions have led to a decrease in the final consumption of the residential sector from 316.7 Mtoe in 2000 to 287.1 Mtoe in 2014 (ODYSSEE, 2016). The noticed improvement in energy efficiency was a result of better thermal performance of buildings, more efficient electrical appliances (air conditioning) and heating systems (condensing boilers and heat pumps). Still, part of this improvement was counteracted by a growing number of electrical appliances, larger homes and the dispersion of central heating which led to an escalation in the average consumption per dwelling by 0.4% per year, compensating 60% of the energy efficiency development reached through technological modernization (European Environment Agency, 2016).

Of the various renewable energy systems that can be installed in the building sector in order to cover energy requirements (electrical and thermal loads), solar energy systems are currently the most widely used, mostly in the form of solar thermal and photovoltaic systems. Especially for the southern countries of the EU, with their high annual solar radiation and temperatures, solar energy systems are already a viable alternative to fossil energy systems and are expected to become even more efficient and cost-competitive in the future (ECOFYS, 2013). Most EU countries of the region enjoy high numbers of new installations annually both in the form of Domestic Solar Hot Water Systems (DSHWS) and of grid connected

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photovoltaic systems, while the biggest potential is expected for renewable combi systems that generate heat for space heating purposes in winter times, cooling through air-conditioning systems in summer and domestic hot water throughout the year.

In Greece, solar energy systems enjoy very high penetration rates both in the form of solar thermal systems as well as in the form of photovoltaics. DSHWS are a mature technology, boasting an installed capacity of 4.3 million m² (3000 MW_{th}) at the end of 2014, placing Greece third in the per capita installed capacity in the EU (ESTIF, 2015).

Although solar thermal systems are a mature technology, up to now most systems were not integrated into the buildings but were installed in available areas with the notion of function over form. Nowadays, architectural integration is a major issue in the development and spreading of solar thermal technologies, especially considering the necessity of their use as a step towards net zero energy buildings. Two integration options are available, façade and roof integration, although still the architectural quality of most existing building integrated solar thermal systems is considered low (Probst and Rocker, 2007).

Another obstacle towards the further diffusion of solar thermal systems for space heating applications is the fact that solar potential is low during the heating period. To overcome this issue energy storage is necessary which can be achieved through three different mechanisms that can therefore be considered for seasonal storage of solar thermal energy as well. These concepts include sensible heat storage, latent heat storage and chemical reaction/thermo-chemical heat storage (Novo et al, 2010). With regard to residential scale thermal storage applications, and particularly those currently used in practice, most of them store energy in the form of sensible heat, while latent and chemical methods are considered promising but not mature enough yet (Schmidt et al, 2004).

The main difference between seasonal and short-term storage systems is located on their size, with the first to be much larger than the second (Brown et al, 1981). More specifically it has been evaluated that storage capacity per unit of collector area should be 100–1000 times larger for seasonal storage than for diurnal storage (Duffie and Beckman, 2013).

Although in the literature a number of studies have dealt with seasonal storage solar thermal systems, through TRNSYS modelling either for large residential buildings (Terziotti et al, 2012) or for a single family dwelling (Sweet et al, 2012), there has been limited work on optimizing these systems while on the same time trying to find the optimum building integration strategies for the solar collector array.

To that end, in the present work, TRNSYS modelling software is used to simulate and optimize a building integrated Solar Thermal System with STES. The model calculates the space heating and domestic hot water needs of a typical 120 m² single-family detached home in the city of Thessaloniki, Greece that has been built according to the latest building code. The contribution of the solar system, as well as the thermal load covered by the auxiliary conventional system is determined and the seasonal solar fraction is calculated. A parametric analysis on the impact of various solar collector areas and types, building integration type, as well as the volume of STES is also presented in order to optimize system design and obtain an seasonal combined solar fraction of at least 40%.

2. Building Topology and Solar System Description

The residential sector in Greece was responsible for 29.4% of the total final energy consumption in Greece in 2012. According to a recent survey, every household in the country consumes, on average, 14 MWh in order to cover its needs. Thermal needs (for space heating and hot water production) account for 73%, while the remaining 27% is needed for the various electrical appliances (Hellenic Statistics Authority, 2013). With the incorporation of the Directive 2010/31/EC in the Greek Regulatory Framework, energy consumption for heating is predicted to decline from an average of more than 100 kWh/m²,yr to as low as 15 kWh/m²,yr (Tsalikis and Martinopoulos, 2015).

As currently more than 86% of all the residences in Greece have a surface area of up to 120m², a south oriented 120 m² detached house with an inclined tiled rooftop, covering the needs of a four-member family, was selected in order to estimate the solar potential from a STES system (Hellenic Statistics Authority, 2014). The building has a rectangular shape with 12 m width and 10 m length, a flat terrace and an internal height of 3 m as presented in Figure 1.

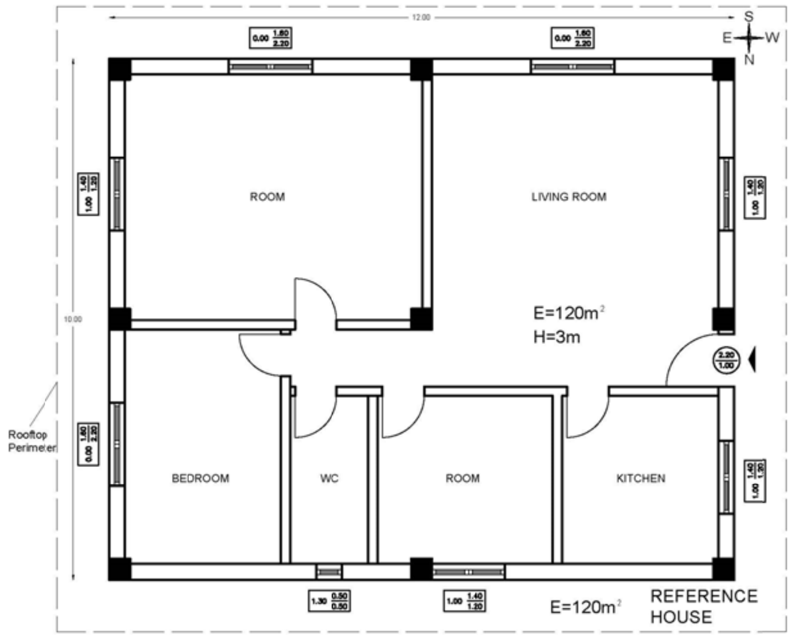

Fig. 1: Plan view of the building

The system under investigation has been designed and simulated in TRNSYS for implementation at a single-family detached home in Thessaloniki, Greece. As a result a weather data file for Thessaloniki city is imported as an external file in Type 109 data reader in the standard TMY2 format. Thessaloniki is located in Northern Greece (40.30°N, 22.58°E), and has on average 1601 to 2200 Heating degree days.

The dwelling is considered to be a single zone structure in order to be compatible with the Type 12a model, which applies the energy / (degree-day) concept. The overall conductance for heat loss from the house (UA value) is defined at 200 W/K (Hellenic Statistics Authority, 2013). It has to be noted that in order to account for the internal gains, the Type 14c component has been used according to the occupancy scenarios and the appliances/lighting used. The temperature at which the house is to be maintained during the heating season is set at 20°C (YPEKA, 2010).

The STES tank is selected to be a water based tank, since water is considered to be a suitable solution performing high heat exchange rates, high thermal capacity and low cost. The tank is equally stratified into five nodes, since this degree of stratification is considered to be a reasonable choice for an effective implementation of such a system. Each node has been set to be 0.6 m height. The secondary storage tank for the hot water for sanitary uses has a volume of 0.3 m^3. As a heating system, low temperature radiators are used, which is the usual choice for this type of systems (Tsalikis and Martinopoulos, 2015).

With regard to the construction materials, the storage tank is considered to be constructed of reinforced concrete. A polyurethane coating system featuring a stainless steel leafing pigment is placed on the top and the vertical inside parts of the tank providing extra insulation. Considering these specifications, the average tank loss coefficient is set to be 1.2 kJ/(hr m^2 K). Two different options of solar collector types were investigated, both flat plate and vacuum tube collectors in various array sizes and inclinations.

The model of the specific system, created in TRNSYS software through the graphical user interface 'Simulation Studio', is presented in Figure 2. Various components, including inputs, parameters and outputs, represent different individual systems. These components are linked together by connecting the outputs of the one to the input(s) of the other(s), modelling the required system. The total system can be separated into four different subsystems.

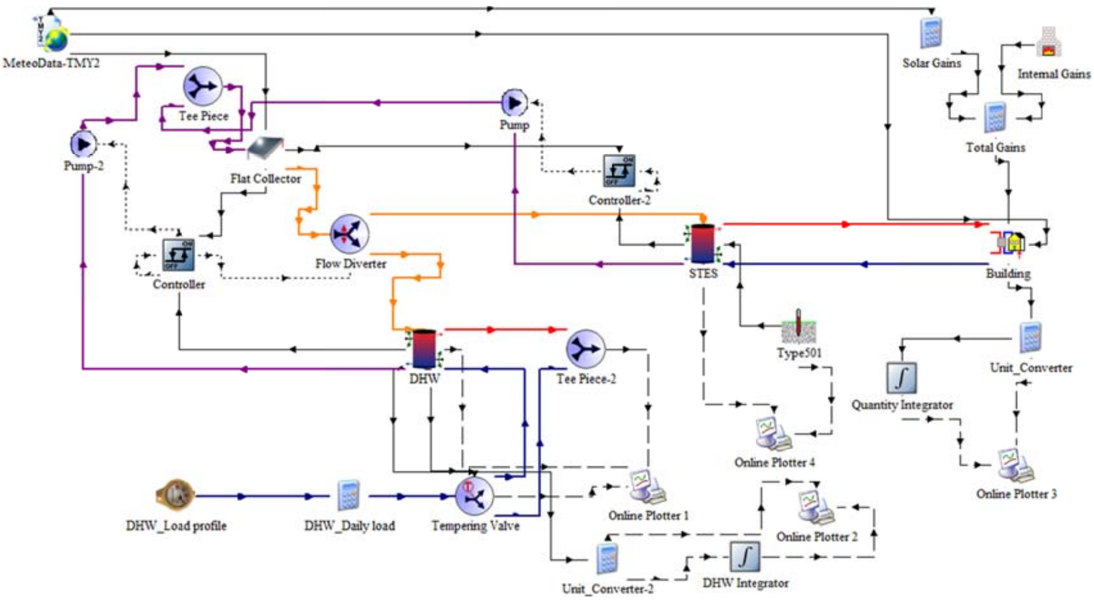

Fig. 2 TRNSYS assembly of the simulation system

The solar collector subsystem consists of the theoretical flat plate collector model (Type 73) or the evacuated tube collector model (Type 71), as well as the other components that participate in the circuits with the domestic hot water and seasonal storage tanks. Regarding their technical specifications, required as parameters in the TRNSYS deck file, for the single glazed flat plate collectors the bottom-edge loss coefficient was set at 0.83 W/m^2K, the fin efficiency at 0.75, while for the vacuum tube collectors the following efficiency coefficients a_0=0.46, a_1=0.802, a_2=0.005 were used.

The collector receives hourly meteorological data as inputs from Type 109 data reader in the standard TMY2 format and charges the two tanks according to the user defined control specifications. Specifically, a differential controller (Type 2) is utilized for each circuit, receiving inputs of the fluid temperature that exits the collector and the temperature of the fluid at the bottom node of the storage tank. The temperature difference between them is compared to the predefined upper and lower dead band temperatures, generating a relative control signal (0 or 1). These output control signals are linked to the pumps, thus switching them on or off, permitting or not the charging of the tanks.

Additionally, a flow diverter (Type 11f) is used to provide charging priority to the DHW tank. Figure 2 depicts its operating principle, where a single inlet liquid stream is proportionally split into two liquid outlets according to the value of an input control function γ. When the value of the output control function of the DHW differential controller (input γ) is 1, the entire flow rate of the collector is rejected to the DHW tank. In other case, when the

DHW circuit's controller output signal is 0, the fluid exiting the solar collector is driven to the STES tank, which is charged if the pump of that circuit is switched on. At any case at most one storage tank is provided with solar thermal energy by the solar collector for each time step. Since two different outputs cannot be linked to the same input, a tee-piece (Type 11h) is used to close the fluid loops with the solar collector, despite of the fact that the two inlet liquid streams are never mixed.

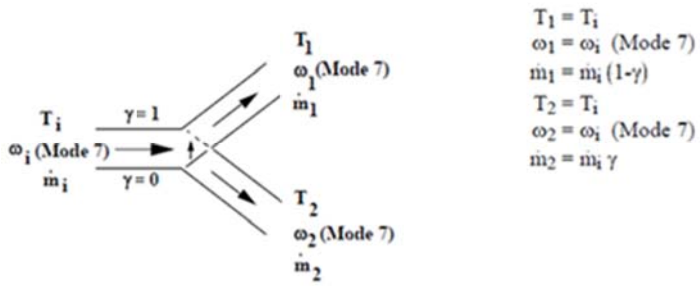

Fig. 3: Flow diverter operation

The DHW tank subsystem includes the relevant stratified storage tank (Type 4c), the components placed to define the daily demand for DHW using Type 14 water draw forcing function, as well as the components used to simulate the contribution of colder fluid that is supplied when the tank flow stream to the load exceeds the required temperature T_{set}. The last operation is achieved with the use of a temperature controlled flow diverter (Tempering Valve - Type 11b). In this case a control function is internally calculated so that an appropriate flow stream displaces fluid of temperature T_h (tank top node temperature), so that the mixed fluid temperature at the outlet of the tee-piece 2 will not exceed the required set point temperature T_{set}. When the thermal energy from the solar collector is inadequate for achieving the minimum required tank temperature, an auxiliary heating element is activated in the tank.

The STES tank subsystem includes a large stratified storage tank (Type 4c) modelling the long-term storage of solar thermal energy during the cooling period for heating application during the thermal period. Since the storage tank is assumed to be buried into the ground, the environment temperature input is linked to the output of the ground temperature model (Type 501). This component is used to predict the soil temperature in a specific depth where the STES tank is considered to be placed.

The building heating load subsystem has been designed to model a building which heating load should be covered during the thermal period. The heating load is partially covered by the STES tank, as well as by an auxiliary heating source with parallel operation when the tank is not able to cover the entire load by itself. Type 12a component, modelling a single zone structure using the energy/ (degree-day) concept, has been used in this case. The user defined specific parameters of the building, such as the overall conductance, as well as meteorological TMY2 input data from Type 109 reader are utilized to calculate the demand for heating and the contribution of each source (STES tank/auxiliary) to meet that demand. The house thermal losses and the possible gains (solar and internal) are calculated for each time step, defining the amount of energy required by the house to maintain the required set point temperature during the entire heating season.

3. Results

The performance of the system is investigated concerning the space heating contribution as well as the DHW load coverage during the heating period. With regard to the heating period, it is always defined as a specific time period during the year, when heating load is on demand. The estimation of this period usually differs from country to country according to the existing meteorological conditions. Actually it also may be diversified for different regions inside a country. The heating period for the city of Thessaloniki, which belongs to the third climatic zone of Greece based on the degree-days for heating (YPEKA, 2010) is assumed as the period from October 18th to April 23th. Therefore this specific period has been set at the TRNSYS control cards and the total heating load (space heating and hot water demand) is calculated at 7660 kWh respectively.

The operation of the system has been examined for two consecutive calendar years in order to achieve steady state conditions. Previous studies have proven that the different initial conditions, concerning the charging or not of the stratified water tanks during the previous cooling period, diversify the simulation parameters of the two years and the final results as well (Antoniadis and Martinopoulos, 2016).

In order to optimize the system, two different type of solar collectors and two different building integration options (which in turn influence the collector array size) are investigated. Initially, a roof integrated flat plate solar array (with an inclination of 35°) was assumed with an installed area ranging from 20 to 40m². As a second option, a vacuum tube solar array was also investigated, either integrated in the façade (inclination of 90°) with an area of either 16 or 20m², or integrated into the roof with an installed area of either 26 or 30 m². Furthermore, the impact from the size of the STES is also investigated, as in all cases the solar arrays are assumed installed with a STES with a volume ranging from 8 to 32 m^3.

Under the conditions stated above the graphic plots of the outcomes obtained from the online plotter 3 for the second year's heating period of October 18th - April 23th are displayed in Figure 4, which presents the instantaneous heating demand (kW), the demand covered by the STES tank (kW), the demand covered by the auxiliary source (kW), as well as the total heating load (kWh) at the end of the heating period and the contribution of the STES tank and auxiliary source (kWh) for the best case scenario (roof integrated 30m² vacuum tube collectors at an inclination of 35° and a STES with a 32 m^3 volume).

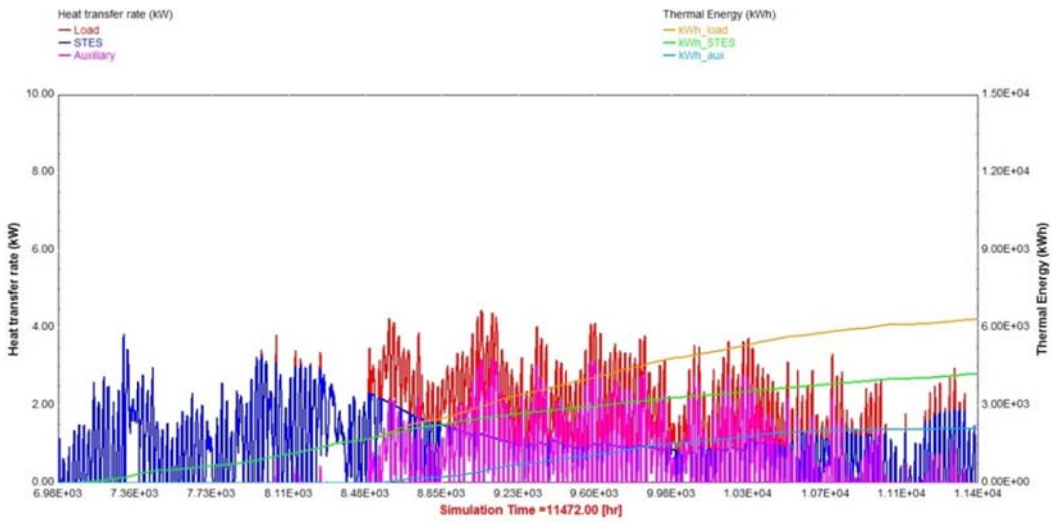

Fig. 4. Heating demand and STES coverage during the 2nd year for the best case scenario

In Figure 5 and 6 the annual coverage for all the options investigated are presented. It is apparent that the impact of the solar collector array is more pronounced than that of the storage tank volume, more so in case of vacuum tube collectors. The results also highlight the versatility of vacuum collectors, as their integration of the building façade doesn't impact the achievable solar fraction, as they are able to cover the same heating needs as a 26m² flat plate collector roof array with only 20m².

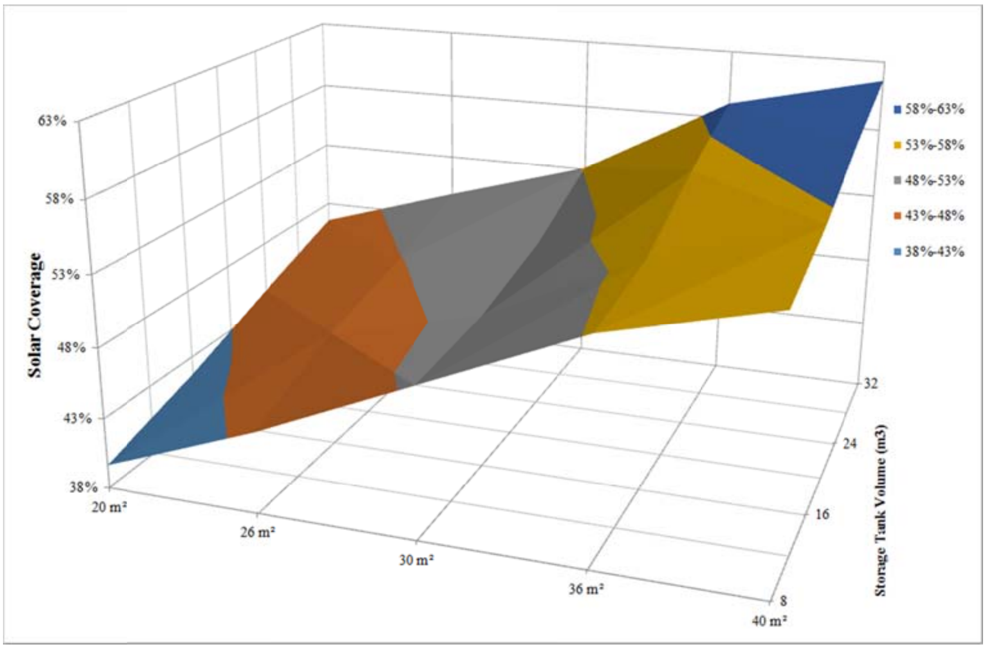

Fig. 5: Seasonal Solar Coverage for roof integrated flat plate collector options

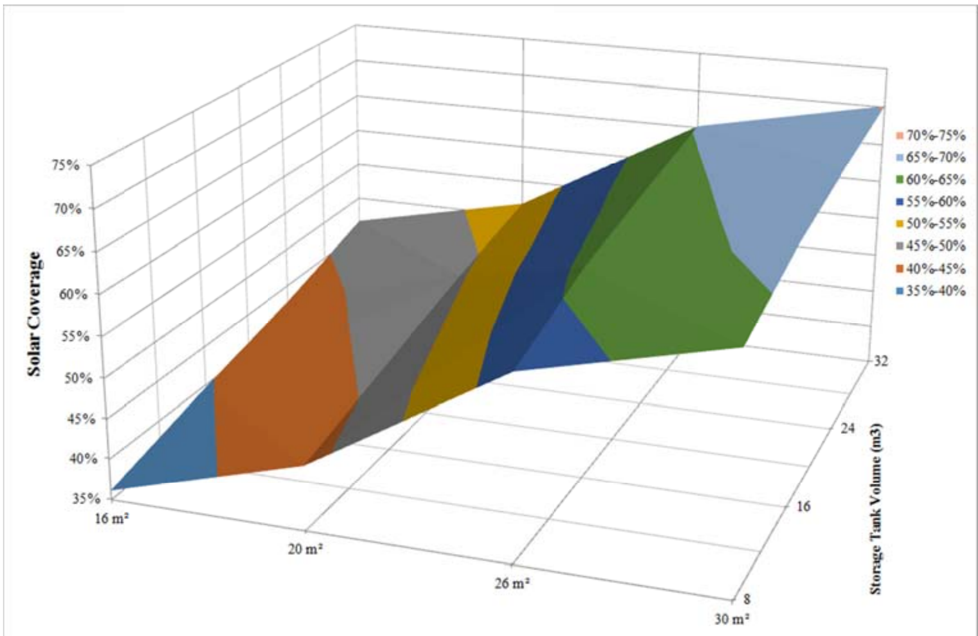

Fig. 6: Seasonal Solar Coverage for façade (16-20m²) and roof integrated (26-30m²) vacuum tube collector options

Taking into consideration, energy demands, initial cost as well as building integration needs, the use of a 20m² vacuum tube array coupled with an 8 m^3 STES is the optimum solution, as it can cover at least 43% of the total heating loads, without presenting overheating issues during summer, while at the same time leaving the roof available for possible integration of photovoltaics in order to cover the electricity needs of the building. The use of façade integrated collectors has the added benefit of a better U value than inclined collectors, because heat losses from the collector are reduced as a result of lower convection levels between the absorber and the glazing, while also the overall U value of the wall façade decreases as well (Weiss, 2003).

4. Conclusions

The performance of a Building Integrated Solar Thermal System which utilizes Seasonal Thermal Energy Storage for domestic applications has been investigated in order to optimize its sizing. The system was able to cover as much as 70% of the heating load requirement for a typical building in Thessaloniki, Greece while also minimizing visual impact.

However the increased heat demand and the extended tank discharge during the winter months make the operation of an auxiliary source in order to meet the entire load neseccary.

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