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Parametric analysis and multi-objective optimization of a solar heating system for various building envelopes

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A R T I C L E I N F O

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A B S T R A C T

The objective of the present work is to investigate energetically and financially a solar assisted heating system for various building envelopes in the climate conditions of Greece. The examined solar heating system includes flat plate collectors, storage tank, boiler and heating devices. The analysis is conducted for the locations of Athens and Thessaloniki which are the most populated cities in Greece. The total analysis is conducted with the TEE-KENAK software which is the official software of Greece for energy audit studies. Different insulation thicknesses are examined (from 0 cm up to 8 cm) and three different glazing scenarios are also investigated. The collecting area is studies from 0 m^2 up to 30 m^2 for all the building scenarios. The results are evaluated energetically and financially. The optimum design scenarios are determined using the net present cost criterion, as well as through a multi-objective optimization/evaluation procedure. Finally, it is found that the optimum design for Athens is the use of 6 cm insulation layer, double glazing (G2 quality) and 30 m^2 solar collectors, while the optimum scenario for Thessaloniki is the use of 8 cm insulation layer, coated glazing (G3 quality) and 30 m^2 solar collectors. The results of this work can be applied for the proper design of the Greek buildings regarding the new buildings and the retrofitting cases.

1. Introduction

The building sector is one of the most energy-consuming domains and it is responsible for about the 30%–40% of the worldwide energy consumption [1,2]. In the United States, the energy consumption in the buildings is the 41% of the total energy consumption, while this amount is 37% for Europe and 28% for China [3,4]. The majority of these energy amounts are produced by the fossil fuels and so it is obvious that there is a need for restricting the high energy demands and for utilization renewable energy sources in the buildings [5]. In this direction, the governments have established legislation rules in order to improve the present situation. For example, the European Union have voted numerous directives with the most characteristic to be the Directive 2009/28/EC [6] about the use of renewable energy technologies in buildings and the Directive 2010/31/EC [7] about the improvement of the building envelopes.

About the renewable energy sources, the use of solar energy seems to be a friendly scenario to the users because it can be converted into useful heat (with solar thermal systems) or into electricity (with the photovoltaic cells) [8]. Especially for countries with high irradiation levels, such as Greece, the combination of solar thermal collectors or/and photovoltaics is a good choice for designing NZEB. Martinopoulos [9] found that the use solar thermal collectors is able to lead to 68% solar coverage and the use of photovoltaics is able to cover the other part of the energy needs in order to create an NZEB for Greek climate. Michopoulos et al. [10] examined a typical building in Thessaloniki and they found that the use of solar energy is able to improve the overall building performance by 54%. Tzivanidis et al. [11] investigated the use of various solar-driven heating systems with and without compression heat pumps and they found that the use of 25 m^2 of solar collectors coupled to a water/air heat pump is the optimum design energetically.

The previous analysis indicates that the use of solar collectors is a suitable way of improving the energetic performance of the building. However, there is a need for improving the building envelope in order to reduce the energy needs of the building. It is essential to state that the energy consumption for heating/cooling in the building is responsible for a great percentage of 60% to 80% of the entire building energy needs [12,13]. The most important parameters of the building envelope are the insulation thickness, the windows area, the ventilation rate and the operation schedule. Bellos et al. [14] found that all the use of insulation up to 8 cm is beneficial for the reduction of the loads, the use of greater windows area is beneficial for the heating reduction while it is not beneficial for the cooling loads. Moreover, Marion et al.

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Nomenclature

A	Area, m^2
A_c	Collecting area, m^2
CC_{ins}	Insulation investment cost, €
CC_{wind}	Windows investment cost, €
C_0	Capital cost, €
E	Energy, kWh
f	Solar cover, –
F	Objective function, –
$F_R(\tau\alpha)$	Zero-order term of the solar collector efficiency, –
F_RU_L	First-order term of the solar collector efficiency, W/m^2K
G_T	Solar irradiation on the tilted surface, W/m^2
h	Heat convection coefficient, W/m^2K
j	Sum counter, –
H_u	Fuel lower heating value, kJ/kg
k	Thermal conductivity, W/mK
K_B	Specific cost of the fuel, €/kWh_{th}
K_c	Specific cost of the solar field, €/m^2
L	Thickness (e.g. insulation), cm
M	Number of layers for the structure component, –
M_B	Fuel mass, kg
M_{CO2}	CO_2 mass, kg
N	Project lifetime, years
NPC	Net present cost, €
OC	Operating cost, €
P	Number of layers, –
R	Equivalent investment years, years
r	Discount factor, %
U	Thermal transmittance, W/m^2K
U_L	Overall heat loss coefficient of the solar collector, W/m^2K
V	Storage tank volume, m^3

Greek letters

β	Collector slope, °
η_b	Boiler efficiency, –
η_{heat}	Heating system efficiency, –
η_{hex}	Heat exchanger efficiency, –
η_{th}	Collector thermal efficiency, –
$(\tau\alpha)$	Transmittance-absorbance product, –

Subscripts

am	Ambient
B	Boiler
B,u	Useful boiler
Floor	Building floor area
fluid	Fluid in the solar field
heat	Heating
in	Indoor
ins	Insulation
load	Heating load
max	Maximum
min	Minimum
out	Outdoor
s	Solar
s,u	Useful solar
wind	Windows

Abbreviations

FPC	Flat plate collectors
NZEB	Nearly zero energy buildings
O&M	Operation and maintenance cost

[15] found that the use of windows to wall ratio is an extremely important parameter for the loads. This parameter has to be different for minimizing the heating and the cooling loads, as well as it is variable among the different cities. Generally, according to their results, it can be said that a ratio of 30% is a reliable choice. Furthermore, Droutsa et al. [16] stated that the most usual retrofitting ways for the Greek buildings are the use of improved windows and the exploitation of solar energy.

The other critical parameter for the building thermal behavior is the insulation thickness which is associated with the overall thermal transmittance of the building cell. Greater insulation ratio leads to lower thermal transmittance and so the building loads are reduced [17,18]. Furthermore, the use of insulation enhances the thermal comfort conditions inside the buildings, something that is extremely important for increasing the productivity of the workers, enhancing the sleeping conditions and increases the living quality [19,20]. Jain and Pathak [21] found that the use of insulation in the buildings is able to reduce the indoor temperature by 4.4 K for hot climate conditions. Moreover, they stated that the use of a reflecting material in the roof is an effective way of reducing loads of the building. Dascalaki et al. [22] found that the addition of extra insulation in the old Greek buildings (construction before 1980) is beneficial for reducing the energy consumption.

However, the use of insulation leads to an increase in investment cost which has to be counterbalanced by the reduction of the operating cost [23]. Papakostas et al. [24] examined various insulation scenarios financially and energetically for the Greek climate and they stated that it is better to insulate properly the building during its construction than retrofitting it later. Martinopoulos et al. [25] studied various heating systems for Greek climate and they concluded that the systems with natural gas boiler are better financially compared to the heat pumps and the biomass boiler. Furthermore, Tzivanidis et al. [26] performed a study about the optimum solar heating systems and the insulation thickness of the building. They found that the optimum insulation thickness is about 6 cm for all the systems according to financial criteria.

The previous analysis indicates the need for constructing efficient building envelopes which presents relatively low heating loads. Moreover, the use of renewable energy sources, such as the solar energy, is an effective way of designing buildings according to the literature studied and the legislative directives. The objective of this work is the investigation of different parameters on the design of a solar-assisted heating system for the climate conditions of Greece. The examined parameters are the collecting area, the insulation thickness and the glazing quality. These parameters are used in order to find the optimum design according to financial criteria. Moreover, a multi-objective optimization/evaluation methodology is applied in order to determine the optimum design with both energetic and financial criteria. The analysis is performed separately for Athens and Thessaloniki which are the most populated cities in Greece and they represent the south and the north climate conditions of Greece. This study is conducted with the TEE-KENAK software which is the official software for building energy audit according to the Greek legislation. Finally, the results of this work can be used for the proper design of the future buildings, as well as for the proper retrofitting of the existing ones.

2. Material and methods

2.1. The examined building

In this work, the examined building has a similar configuration in every case. Only the insulation thickness changes and the glazing type