Review of an innovative thermal and economic model of a thermal solar source

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Abstract. This paper presents an innovative calculation method that simplifies the present calculation in the existing Romanian solar methodology, but also brings a new approach to the problem of determining the actual efficiency of a heating system using solar panels during the actual hours of sunshine. This new method will also make better economical estimations by including a new calculation method that is adapted strictly to solar panels applications. Both proposed methods, include a new approach of determining the thermal and economic indicators faster or more precise. The results shown in this article, validate the new calculation method and offer new perspectives on real-time hourly solar system performance evaluation. Those results show that although the actual hourly efficiency of the solar panels increases over a small period of time, daily system efficiency that includes the consumer's heating needs, decreases due to the limitation of the required thermal energy over a longer period of time that exceeds those sunshine hours. This paper provides a new vision regarding the way solar systems are treated and suggests some adjustments that need to be made in calculating the solar systems. Thus, due to a considerably higher heat input over a given period of the day, it is concluded that these systems work much better in the case of extra storage of this energy (larger storage tank) or by adjusting the indoor temperatures (through automation) during this solar charging regime.

1. Introduction

Energy resources contribute to the economy of any country and play an important role in improving the standard of living. The importance of energy resources is evident in almost all aspects of development and history shows that there is a very close relationship between energy resource management and economic activity. The use of energy from renewable sources [1], in particular solar energy in residential building applications, has gained widespread popularity globally, fulfilling the goals of sustainable development and environmental conservation [2]. The policies of the European Union support the deployment of technologies using renewable sources and introduce certain minimum thresholds for their use [3]. As a member country of the European Union, Romania has the obligation to respect them and to invest in the development of this energy segment.

The high interest in renewable energy [4] has increased due to the global policy of replacing the "classic" resources that can be exhausted by raw materials. For this reason, the challenge is to achieve a better conversion rate of solar radiation into energy.

Increasing the overall efficiency of a solar panel system [5] by improving energy capture but also by storing it more efficiently will result in the replacement of non-renewable energy systems with new sources.
In other words, the basic problem of the current systems is to achieve a good cost / benefit ratio [6]. However, at the country level there is no energy assessment that can lead to a national assessment of the thermal potential for various configurations of solar thermal panels.

Current studies, like [7] and [8], have shown that solar panels can be successfully used in the preparation of thermal energy serving a residential consumer. However, in [9] it is shown, that on the Romanian territory there are five climatic zones of calculation (according to national regulations), and the values of the external temperature and the solar intensities differ from area to area (Table 1). This underlined the need for a national study to provide an overview of the country. Equally, the question of the profitability of these solar systems is compared to other systems that use unconventional energy sources or conventional fossil fuel sources.

Table 1. External Temperatures of the five climatic zones in Romania [10]

| Climatic Zone | External Temperature (°C) |
|---------------|---------------------------|
| 1             | 12                        |
| 2             | 15                        |
| 3             | 18                        |
| 4             | 21                        |
| 5             | 25                        |

This paper aims to estimate the ability to use solar panel systems to produce the thermal energy needed by a residential consumer. From a thermal point of view, this is achieved by determining the coverage levels of the solar installation and the yields [11] of the solar installation and economically, the specific costs of the installation and the recovery time of the investment has to be determined.

National technical regulations and European standards that use the solar energy for solar thermal panels are as follows:

SR EN 15316 / 4-3 - Energy performance of buildings - Method of calculating energy requirements and system efficiency - Part 4-3: Heat generation systems, solar thermal systems and photovoltaic systems Module M3-8-3, M8-8-3, M11-8-3;
SR EN 15316 / 6-6 - Energy performance of buildings - Method of calculating system energy performance and system efficiency - Part 6-6: Explanation and justification;
SR EN 15316-4-3 Module M3-8-3 M8-8-3;
MC 001/2006 - Methodology of Energy Performance Calculation;
Annexes MC 001/2006 - Energy Performance Calculation Methodology;
SR 4839 / 2014- Heating installations, Annual number of degrees-days.

In this paper, the steps from a proposal for the revised MC-001 for the determination of solar systems are used for energy determinations.

2. Method description

The calculation method presented, applies to residential or non-residential buildings that use solar energy storage for space heating and hot water supply.

The solar energy system is typically composed of a loop containing the solar energy capture surface and a heat exchanger immersed in an accumulation tank or placed outside the tank. If the heat sink of
the solar loop is placed at the bottom of the tank, the heat exchanger of the back-up source is based at the top of the tank. The thermal agent prepared in the storage tank is the thermal agent used in the consumer's central heating system if the utility is heating or hot water delivered to the consumer.

The solar collectors used, can be flat-plate collectors or vacuum tubes. The storage tank generally has a volume that allows the consumer to take advantage of most thermal energy captured by the solar loop diurnally.

2.1. Thermic model

The method of assessing the energy performance of a plant using the solar energy used is a monthly method described in [6] which permits each month of the year and throughout the year or season to assess the energy performance.

The method of assessing the energy performance of the solar plant for space heating and the method of assessing the energy performance of the solar plant for domestic hot water production have a number of common elements in each of the three mentioned steps and the differences will be presented independently. The common aspects will be presented together.

This method is a so-called monthly method [12] that permits each month of the year and throughout the year or season to assess the energy performance.

The method involves in the first step the sampling of a constructive-functional information about the solar energy capture surface, the pump and the heat exchanger within the solar loop. Information about the hot water or space heating consumer is also required, such as daily consumption, heating surface and sizing temperatures, etc. An important and distinct category of data is climatic data on outdoor temperatures and the intensity of solar radiation.

Once this data is known, it is proceeded to the second step - the application of the actual method, by evaluating some intermediate parameters that will continue to allow effective evaluation of the energy performance of the solar energy installation every month of the year and season and whole the year. The third stage consists of assessing the energy performance of the system that is represented by the solar loop capture efficiency, the energy coverage offered to the consumer and the monthly, seasonal and yearly solar incident energies.

For the first step, the following data was used to determine the system configuration output:

a. The SC- variable solar surface area of the collector with the H / (kc ∙ Sc) ratio (constant);

b. The geometric correction factor of the captured heat flux, F ′;

c. Global heat transfer coefficient of solar collectors, kc;

d. Solar collector glazing element coefficient of absorption, α;

e. The coefficient of transparency of the collector glazing element, τ;

f. Angle of inclination from the horizontal plane of the collectors, φi;

g. Deviation angle of the orientation of the capture surface to the South, φa;

h. Heat exchanger surface in the solar loop, Ss;

i. Storage tank volume, V = V / Sc;

j. The global heat transfer coefficient of the heat exchanger in the solar loop, kS;

k. The flow rate of the heat transfer medium into the solar loop, GC;

l. Surface of the central heating system, SINC;

m. The nominal temperatures of the heating agent at the sizing of the system, t0, tR0, depending on the type of installation used, the hot water temperature and the cold water temperature;

n. Intensity of solar radiation, monthly averages, for a horizontal capture area, I0, according to the Mc001 methodology from 2006;

o. Average monthly temperatures according to SR 4839/2014;

In step two of the calculation of the intermediate calculation parameters, the following factors for the calculation of the heating case are determined:

Firstly, the solar panel factor is determined:
\[ E_C = \exp\left(\frac{F^c \cdot k_C \cdot S_C}{1,163 \cdot G_C}\right) \]  

(1)

Afterwards, the exchange rate factor is determined:

\[ E_S = \exp\left(\frac{k_S \cdot S_S}{1,163 \cdot G_C}\right) \]  

(2)

A factor that relates those two in order to determine the primary thermal loop is determined:

\[ E_{CS} = \frac{E_C \cdot (1 - E_S) + E_S \cdot (1 - E_c)}{1 - E_C \cdot E_S} \]  

(3)

In order to determine the secondary loop with the consumer, the average distribution temperature is determined:

\[ t_{m0} = \frac{t_{T0} + t_{R0}}{2} \]  

(4)

The consumer thermal resistances are determined:

\[ R_{11} = \frac{t_{m0} + t_{e0}}{t_{T0} + t_{e0}} \]  

(5)

\[ R_{12} = \frac{t_{m0} - t_{e0}}{t_{T0} - t_{R0}} \]  

(6)

In order to find the consumer global thermal coefficient:

\[ H = \frac{S_{inc}}{R_{inc}} \cdot R_{11} \]  

(7)

And the thermal flow for the specific consumer:

\[ G_{INC} = \frac{S_{inc}}{R_{inc}} \cdot \frac{R_{12}}{1,163} \]  

(8)

Then, the first factor that fully determines the primary loop is calculated:

\[ F_R^B = \frac{1,163 \cdot G_C}{k_C \cdot S_C} \cdot (1 - E_{CS}) \]  

(9)

The second factor that relates the consumer to the powerplant is calculated:

\[ F_R^C = 2 \cdot \frac{H}{S_C \cdot k_C} \cdot \frac{t_{e0} - t_{T0}}{t_{T0} - t_{R0}} \]  

(10)

And the factor that includes those 2 is calculated:

\[ F_R^{BC} = \left(\frac{1}{F_R^B} + \frac{1}{F_R^C}\right)^{-1} \]  

(11)

Then, the overall factor of the heating and the utilization factor of the heating system are determined:

\[ F_{INC} = \frac{t_{R0} - t_{e0}}{t_{e0} - t_{T0}} \]  

(12)

\[ f_u = 0.35 + 0.71836 \cdot \exp\left(\frac{-0.1 \cdot 75 \cdot S_c}{V_a}\right) \]  

(13)

Similarly, factors are calculated for the case of domestic hot water preparation.

In the 3rd calculation step (determination of energy parameters), calculations are made to determine the monthly coverage and overall plant yield using the relationships:

The most important factor that is dependent on the climate, \( \beta_{REF} \) is determined with the formula:
\[ \beta_{\text{REF}} = \frac{I_{10} + I_e}{I \cdot n} \]  

Where I, is calculated from the overall horizontal I found in the MC001 methodology for the specific azimuth, and is being multiplied with a factor of sunshine (n) depending on season, that is 4,5 for Winter or 3,5 for Summer. This factor represents better the model where the solar panels use a higher solar radiation just for a couple of hours instead of using the average found in the methodology.

Then, with this factor included, the actual efficiency of the solar panel can be calculated:

\[ \eta_{\text{CC}} = F_{R}^{BC} \cdot \left[ (\alpha \cdot \tau) - k_c \cdot F_{\text{INC}} \cdot \beta_{\text{REF}} \right] \]  

The relation that determine the thermal collector power is:

\[ P_{CP} = S_c \cdot I \cdot \eta_{\text{CC}} \cdot f_u \]  

And the total energy produced by the solar panels in 24 h, during a number of days (N) is calculated with:

\[ E_{CP} = P_{CP} \cdot 24 \cdot N_{cl} \]  

The electric power consumed by system is considered a part of a pump power:

\[ P_{\text{EL}} = 0,25 \cdot P_p \]  

With those relations, the energetic values of the primary loop of the system is known.

### 2.1.1. Determining the heating case

The consumer power is determined with the relation:

\[ P_{\text{CONS}} = H \cdot (t_{10} - t_r) \]  

For the thermal analysis of the heating case, it is determined a coverage level for each month and the entire year with the formula:

\[ G_{\text{ur}} = \frac{P_{op}}{P_{\text{cons}}} \]  

Similar, the efficiency in the case of heating is determined each month on average the entire year, with:

\[ RND = \frac{P_{cp}}{P_{l}} \]  

### 2.1.2. Determining the hot water preparation

Similar to the heating case, it is used the same methodology, but the equations related to the consumer power are different. The consumer power is determined with the relation:

\[ P_{\text{CONS}} = 1,163 \cdot G_{\text{CONS}} (t_e - t_r) \]  

For the thermal analysis of the preparation of hot water case, it is determined a coverage level for each month and the entire year with the formula:

\[ G_{\text{ur}} = \frac{P_{op}}{P_{\text{cons}} + P_{\text{el}}} \]
The efficiency in the case of preparing the hot water supply is determined as in the case of heating, with:

$$RND = \frac{P_{qp}}{P_i}$$

(24)

2.2. Economical model

Under existing and ongoing proposals and methodologies, an economic calculation is described that addresses all of the solutions based on renewable resources. The economic study has customized the calculation formulas and has adapted them to the requirements of the research objectives.

The economic analysis of a new solar investment for existing buildings is done through the economic indicators of the investment. Among the most important are the following:

• the updated net value of the additional investment due to the implementation of an energy rehabilitation / modernization project and the energy savings resulting from the implementation of the mentioned project (RON);

• duration of recovery of the additional investment due to the implementation of an energy rehabilitation / modernization of the project (years), $N_R$, representing the time elapsed since the investment was made in the energy modernization of a building and when its value is equal to the value of the savings achieved through the implementation of the measures of energy modernization brought to the initial moment of the investment;

• the cost of the saved energy unit is [RON/ kWh], representing the ratio between the amount of additional investment due to the implementation of a rehabilitation / energy modernization project and the energy savings achieved through its implementation during the recovery period of the investment.

Those indicators will help in the global evaluation of future investments in solar panels.

Depending on the values of the aforementioned economic indicators, resulting from the analysis of the various energy modernization, the following measures will be chosen:

• Net updated value, with negative lifetime estimates for the energy modernization measures analysed;

• investment recovery time, smaller and no longer than a reference period, imposed on economic or financial grounds (by creditor or investor) or technical (estimated lifetime of the energy modernization solution);

• the cost of the saved heat unit is as low as possible and not higher than the projection at the time of the investment of the current cost of the heat unit.

The basic procedure for comparing the technical and economic effects of the application of the various energy efficient solutions in construction is the analysis of the net updated value of the costs involved in realizing the investments and exploiting the related facilities.

Net Actual Value (VNA) is the projection at time “0” of all the above mentioned costs, depending on the depreciation rate of the currency considered, in the form of the annual average depreciation.

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For public sector projects (social, cultural, administrative buildings), the depreciation rate of the currency varies between 0.1 and 0.07 with the tendency to lock on the second value. For the private sector (large corporations, banks) the assumed depreciation rate exceeds 0.1. Finally, in the case of housing construction, the annual depreciation rate of the coin is in the range of 0.04 - 0.07. Significant differences between these values clearly reveal a national policy to promote energy conservation projects, especially for domestic consumers. Low values of the currency depreciation rate, favors the rapid promotion of technical conservative energy solutions. Therefore, the high values of the depreciation of the currency for investments in the public sector or in the private sector that record important turnover offset the relatively low value (0.04) applied to the housing sector.

Maintenance costs represent a minor share in the structure of the relationship (25) and, if they cannot be appreciated, they can be ignored.

Taking into account the above, the relation (25) was used in the VNA calculation in the simplified form:

$$VNA = C_0 + \sum_k C_{Ek} X_k$$  \hspace{1cm} (26)

In which:

$$X_k = \sum_{t=N}^{\infty} \left( \frac{1+f_k}{1+i} \right)^t$$  \hspace{1cm} (27)

In order to determine the duration of recovery of the solar system investment, two VNA values specific to a classical solution and a conservative energetic solution are analysed in parallel and having both equipment with an equal lifetime, N, the VNA related to the additional investment due to the implementation of the energy modernization projects and energy savings resulting from the implementation of the mentioned projects:

$$\Delta VNA_{(m)} = C_{(m)} - \sum_k \Delta C_{Ek} \cdot X_k$$  \hspace{1cm} (28)

In which:

$$\Delta C_{Ek} = c_k \cdot \Delta E_k$$  \hspace{1cm} (29)

The condition that an investment (in the energy modernization solution) to be efficient is the following:

$$\Delta VNA_{(m)} < 0$$  \hspace{1cm} (30)

The duration of the extra investment recovery due to the implementation of an energy modernization project NR is determined by replacing the life expectancy with NR as an unknown value in relation (28) as explained in relation (25), and by imposing the condition for recovery of the investment:

$$C_{(m)} - \sum_{k=1}^{\infty} c_k \cdot \Delta E_k \cdot \sum_{t=\infty}^{\infty} \left( \frac{1+f_k}{1+i} \right)^t = 0$$  \hspace{1cm} (31)

The cost of the unit of energy saved by implementing the solar system (or the cost of a saved kWh) is determined with the relation:

$$e = \frac{C_{(m)}}{N \cdot \Delta E}, \text{ (Euro/kWh)}$$  \hspace{1cm} (32)

With regard to the additional investment $C_{(m)}$, projected at year "0", two possible scenarios can be imagined as follows:

a. The investment beneficiary has the full amount at the time "0", in which case the $N_B$ corresponding to the investment coincides with the value $C_{(m)}$;

b. The investment beneficiary does not have the amount necessary to make the investment, in which case a loan, repayable in a $N_c$ year with a fixed annual interest, is used. d. The requisite loan condition is $N_c < N$, followed by duration (N) to show the net benefit of implementing energy modernization solutions.
The economic indicators on which the economic efficiency analysis of the energy modernization solutions applied to existing buildings is based are the specific cost.

- The specific cost of the amount of heat saved is determined with the relation:

\[ e = \frac{C_{INV}(m) \cdot \Delta \beta}{N_S \cdot \Delta E_I}, \text{ (Euro/kWh)} \]

(33)

The relation (33) was used to estimate the cost of upgrading to solar installations, as a complement to the conclusion resulting from the evaluation of the duration of the recovery of the investment.

3. Results

Both outputs of the thermal and economic studies will be presented below.

3.1. Thermic results

The calculation method used (that was presented theoretically), applies to residential or non-residential buildings fitted with solar energy storage and use facilities for space heating and hot water.

In order to do the simulation, a consumer with a \( H = 16000 \text{ W/K} \) for heating and a \( H = 689 \text{ W/K} \) for the hot water supply where used. This correspond to the need of energy of 80 apartments for the heating and hot water supply. The monthly intakes of solar energy where calculated and they showed how much renewable energy this kind of system could produce. The monthly coverage levels as well as monthly efficiency are shown in this article in order to fully express the solar usage for the specific consumer.

This study used a \( k_c = 2.3 \) and 4 for 3 types of thermal solar panels with the following characteristics: \( F' = 0.9; \alpha = 0.9; \tau = 0.85; G_C = 50 \text{ l/m}^2 \text{h}; \nu = V/S_C = 50 \text{ l/m}^2 \). For the heat exchange the following were used: \( S_S = 0.1 \cdot S_C \) and \( k_S = 600 \text{ W/m}^2 \text{K} \).

Nominal heat temperatures for the heating system are as follows, \( t_{T0} = 50 \text{ °C} \) and \( t_{R0} = 30 \text{ °C} \) for one case, \( t_{T0} = 70 \text{ °C} \) and \( t_{R0} = 50 \text{ °C} \) (the * case in figures) for the second case; the hot water temperature was 60 °C for one case and 50 °C for the second case (the * case in figures) and the cold water temperature was considered constant throughout the year at a temperature of 15 °C.

For 5 cities, representing each, one climatic zone, the solar radiation intensities, monthly averages, for a horizontal capture area, \( I_o \), were taken for all the months of the year, according to the Mc001 methodology. Average monthly temperatures for all the months of the year were taken according to SR 4839/2014.

The values chosen for the \( H / (k_c \cdot S_c) \) are chosen to be 15 for heating and 4 for the preparation of hot water supply. This was done to represent as realistic as possible a solar investment for the chosen objective. Thus, for heating, due to very large capture surfaces, a higher ratio value was chosen. For domestic hot water, a lower value was chosen to provide a higher degree of coverage at smaller capture surfaces.

The following results were obtained for heating:

Fig. 1. Degree of coverage calculated for heating
Fig. 2. Efficiency calculated for heating
As it can be seen in figure 1, the coverage levels are generally lower with every climatic zone, the zone 4 city is an exception because of the necessity of heating during Summer when the solar panels work at the highest efficiency. The results obtained in this study encourage using this type of heating solution in order to supply 20% to 30% of the needed energy.

Figure 2 shows that those solar systems have a general efficiency above 40%, up to 55%, in the case that was chosen.

The following results were obtained for the preparation of domestic hot water supply:

3.2. Economic results

Similar to the thermal simulation, the economic simulation uses the economical calculation method (that was presented theoretically) and it applies to residential or non-residential buildings fitted with solar energy storage and use facilities for space heating and hot water.

The economic factors were determined according to the cases and consumer presented in the thermal study. The prices of the solar panels where estimated as an average of those currently on the market. The prices for energy costs were estimated as the latest. Maintenance costs were considered.

The following results were obtained for heating.
The investment for the heating case, can recover in less than 10 years if the state will help developing this area and producing renewable energy. Generally, the investment can recover in less than 20 years, which is considered the maximum life period of this system.

The specific cost for heating is less than 1,2 euro/kWh and can be as low as 0,4 euro/kWh depending on the area of investment.

The following results were obtained for the preparation of domestic hot water supply:

Contrary to the heating case, the recovery time for the preparation of the hot water is very low. It is lower than one year for all cases. This suggest that all consumers must apply for this solution if they have the money for the investment.

The specific cost for the investment in preparation of the hot water supply using solar panels is less than 0,03 euro/kWh.

4. Conclusions

The study in this paper made possible to get an overview of the possibilities of solar investments, showing a method that can be applied in Romania or other countries to make initial assumptions.

Creating a database for the whole of Romania, depending on the variation of the main factors, using this method of calculation is possible. This study also includes the possibility of using different configurations of thermal solar panels on the territory of Romania.

Thus, the innovative calculation method used in this paper, simplifies the present calculation in the existing methodology, but also responds to a new approach to determining the actual operating behaviour of the solar panel system during actual sunshine hours. This proposed method, with simplifying assumptions (that all monthly methods have) can improve the monthly calculation method by getting more values to reality. This has the advantage of determining the coverage rates and more accurate annual results (resulting from the research) for the case of heating and can also be used successfully for the preparation of hot water.

By modifying the average hourly solar intensity, new possibilities are created for assessing the actual hourly efficiency of solar installations. Thus, it can be noticed that although the actual hourly efficiency of the installation increases over the year, the hourly efficiency of the system that includes the heating needs of the consumer decreases due to the limitation of the required heating energy. These conclusions provide a new insight into the way solar systems are treated and suggest some changes that need to be made in the sizing of solar systems. Thus, due to a considerably higher heat input over a certain period of the day, it is concluded that these systems work much better in case of additional storage of this energy (higher storage tank) or by introducing higher adjustment temperatures (by automation) during this solar charging regime.

The values of the annual coverage rates of the plant using the monthly sunshine period are higher, and the differences between the different setting temperatures decrease. Annual efficiency increases to
the same extent, especially for the winter, due to the fact that the plant works better for a shorter period of time and the energy is stored in the storage tank.

In the energy study, it is concluded that there may be solar configurations that generate a heating energy saving needed to heat residential buildings in the case of easy installation of these systems in most homes. This value can be considerable and can lead to greater energy independence of Romania. For hot water preparation, solar panel systems can fully provide the energy demand, being more efficient and less restrictive than heating.

The economic study presents a new, simplified calculation method that has been adapted and can only be used to determine the main economic indicators needed in calculating solar systems. This comes as a complement to the existing methodology and serves to help all those interested in using solar systems (Romanian state, users, designers, etc.).

An economic analysis that uses the innovative method of energy determination of thermal solar installations can lead to much lower recovery times for the heating case. This would encourage investments in such systems at national level for both heating and domestic hot water.

The energy and economic analysis presented in this paper, which addresses the use of solar energy systems for the preparation of thermal energy serviced by a residential consumer, has given a way to demonstrate both the capabilities and limitations of these systems used on the territory of Romania. This paper provides the basis for improving the existing methodology and can be developed further into new simplified calculation methods for the energy and economic calculation of thermal solar systems. The new method may include simplified nomograms that reduce computational times and complexity, benefiting from a degree of acuteness in terms of computational values obtained from the current method used in the methodology. This can be further developed by replacing the additional fossil fuel source with a thermal source that also relies on renewable energy sources of heat.

Both methods presented in this paper, include a new approach of determining the thermal and economic indicators for a heating and a hot water preparation system that receives energy from solar panels.

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