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Research on unconventional hybrid heat supply systems
for buildings

PhD Thesis
ABSTRACT

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1. INTRODUCTION

The burning of fossil fuels was the main source of mechanical, thermal or electrical energy production in the XIX and XX centuries. The planetary exploitation of these resources has affected the environment and leads to the depletion of resources in the coming decades. According to [7], the deterioration of the ozone layer and the accentuation of the greenhouse effect by producing greenhouse gases resulting from the processes of burning fossil fuels is the main problem of the XXI century.

In this respect, attempts are being made to find the most efficient such systems, replacing in an increasing proportion, energy resources based on fossil fuels [46].

1.1 The exploiting potential of renewable solar resources

The use of solar energy for space heating and domestic hot water preparation is now an increasingly common solution to achieve energy savings from renewable resources [37]. In this thesis, it was aimed at experimentally establishing the technical performances of a solar collector. Determining them with the highest degree of confidence is a crucial factor in determining the overall performance of a system [27] that incorporates such equipment. In the specific literature there are several variants by which this solar performance was determined from a theoretical point of view, according to [13]. Most of the methods of determination for all types of solar panels (flat plate or vacuum tubes) can be based on the theoretical relationships in [34]. The differences in the efficiency of different types of solar panels are notable [19], but also their cost of manufacture varies greatly [40]. It is presented in the literature through different types of equations, those of the first degree having a lower accuracy than those of the second degree [12].

In [34] the general calculation method is presented, applicable to residential buildings where the temperature of thermal energy delivery is at least 20 °C. This method is called f-Chart. For water or heating air systems, the diagram in Figure 1 is used, where the synthetic factors X and Y have been previously described. Next, one can determine the optimal ratio between the storage capacity and the heat transfer capacity of the heat exchanger and a brief economic analysis showing the variation of the capture surface from the degree of energy coverage of the solar panels.

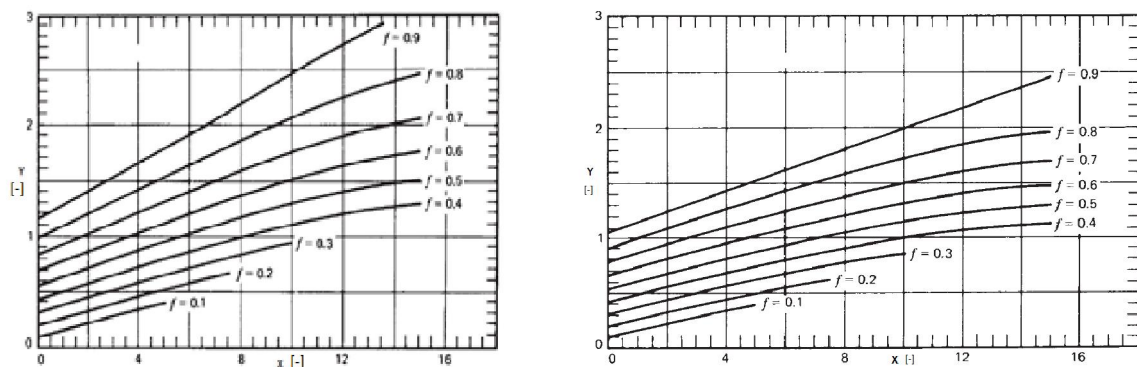


Figure 1 a,b - F-Chart method for heating systems on water(a) and air(b)

1.2 The exploiting potential of heat pump equipment

The heat pump is also a complex thermodynamic installation through which the natural direction of heat transmission can be reversed. It has at least two external sources: the cold source, which takes the heat from the outside and gives it out through the heat exchanger-evaporator, and a hot source, which takes the heat from the working agent in the condensing heat exchanger and gives it out outside [18].

The use of heat pumps can also provide a significant contribution to covering heat demand in residential buildings, being a very versatile and common renewable energy source, therefore, it is a suitable energy source for low-energy homes and passive houses [37].

1.3 Description of the system studied

This PhD thesis studies an advanced way of using a mixed system using solar panels and heat pumps. This unconventional system of using solar thermal energy is used for heating the premises of a building and preparing hot water for consumption. From the point of view of the general scheme of operation, solar panels introduce thermal energy into a heat accumulation system represented by a well-insulated thermally insulated tank. A heat pump, introduces thermal energy into the same accumulation tank, which is fed to the heating system of a dwelling.

This summary of the thesis aims to assess the energy performance of such a hybrid system (Figure 2) of the use of solar energy and presents the direct consequences regarding the optimisation of these systems by selectively treating only the case of preparation of the heating agent.

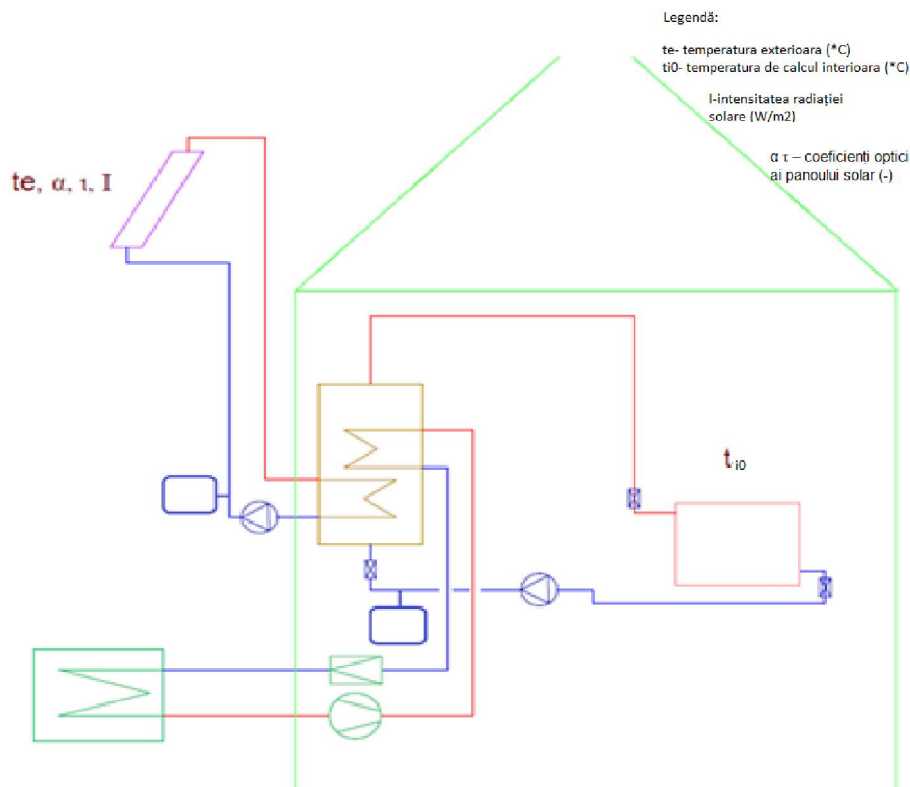


Figure 2 - General scheme of the installation with climatic factors

The main objective of the thesis was to achieve practical and easy-to-understand and applied ways of the thermal solar chapter within Mc001/2021 [36], by developing and customizing the relationships within this chapter of the energy methodology. Given that the annual energy coverage of the thermal energy needs is the element sought to be evaluated, the structure of this parameter has been studied and it has been observed that it, GAE depends on a series of independent parameters, known to the user such as: the energy indicator of the climatic potential of the locality to which the investigated building belongs (β_{REF}), the sizing of the heating installation (t_{T0}/t_{R0}), the type and number of solar catchers reflected by (k_c), respectively by the ratio of the abstraction surface (H/S_c). For this reason, the 79 localities mentioned in SR-4839/2014 [44] were classified, in 5 different classes depending on the β_{REF} , calculating the β_{REF} for each of the 79 localities. In this way, for each of the 5 classes, for the average class value for β_{REF} , the expression of GAE was found for each specific case. Further, for each class, even more particular forms of GAE were obtained for 3 variants of sizing the central heating installation (t_{T0}/t_{R0}): 90/70 °C, 70/50 °C and 50/30°C and consequently, $5 \times 3 = 15$ particular forms of GAE appeared depending on climatic factors and the chosen type of heating, which, however, still depends on 2 independent parameters, which are k_c and H/S_c , as explained above. For their integration, a series of simple graphics were used from which GAE emerges. From this point on, it is proposed as an alternative to switch to an economic analysis that takes into account both the quality of solar capturers (k_c) and the quantity of solar catchers (H/S_c). If the solar collector area is known, then GAE is actually established and the economic analysis can be determined depending on the initial investment cost. For the use of heat pumps in tandem with solar thermal panels, the COP and energy consumed by a heat pump system to ensure the entire heat needed only from renewable energies were calculated. The economic analysis was complemented by the economic calculation of the entire system from solar panels and heat pumps.

In addition to this objective, the thesis aims to ease the work of the designer of renewable systems, integrating a guide for the use of the thermal solar calculation methodology, calculation graphics from which GAE is directly evident, both for the heating systems usually encountered and for the hot water preparation systems.

In order to achieve these goals, a series of in-depth studies have been carried out using the bases of solar calculation methodology, which show the importance of evaluating all the simple parameters of which GAE is composed. The study of heat pumps led to the realization of mixed systems of overall for the supply of thermal energy to residential buildings.

This PhD thesis includes the studies of 3 research reports that treated theoretical research, experimental research and a calculation model for determining the performance of mixed systems using solar panels and heat pumps.

2. MATHEMATICAL MODELLING OF THE FUNCTIONING OF UNCONVENTIONAL SYSTEMS

2.1 Fundamental equations

In this summary of the thesis, which aims to use an experimental system of solar panels (together with a heat pump system), the main relations of calculation of such a system, taken from the bibliography, according to [18], [19] and [34] will be presented].

It is chosen for modeling, the system shown in Figure 2.

2.1.1 Solar loop-specific thermal balances

According to [13], the relationship that allows the measurement of the capturer's performance is:

$$\eta = F_R \cdot (\alpha \cdot \tau) - F_R \cdot k_C \cdot \beta \quad (1)$$

Where, β is the climatic factor that is determined with:

$$\beta = \frac{t_0 - t_e}{I} \quad (2)$$

And F_R is the capture efficiency of the solar panel, determined with:

$$F_R = \frac{a \cdot \rho \cdot c}{k_C} \cdot (1 - E) \quad (3)$$

E is the intrinsic, constructive-functional characteristic of the capture surface:

$$E = \exp\left(-\frac{F' \cdot k_C}{a \cdot \rho \cdot c}\right) \quad (4)$$

2.1.2 Heat balances specific to the heat pump loop

From the theoretical studies [24] and [25], it concludes that the central indicator to be determined for heat pumps is the maximum efficiency of the refrigeration machine, ε_{vpi} , all the efficiency is determined from it and the construction constants of the heat pump.

In order to determine the ε_{vpi} , within the chosen system, the vaporization and condensation temperatures must be established:

$$T_{VP} = t_{VP} + 273,15 = \theta_{VP} - \Delta t_{VP} + 273,15 \quad (5)$$

$$T_{CD} = t_{CD} + 273,15 = \theta_{CD} - \Delta t_{CD} + 273,15 \quad (6)$$

By performing these calculations, a dependence ε_{vpiz} is obtained in relation to the nonlinear condensation and vaporization temperatures (T_{CD} and T_{VP}), which has a lower degree of accuracy in determining the value curve. For this reason, it was opted to use a more precise, similar method, which expresses the ε_{vpiz} according to the ε_{vp}^C , the Carnot efficiency of the refrigeration machine, through a linear equation. In this case, T_{CD} and T_{VP} remain the same and the equations of the form are obtained:

$$f = \frac{T_{CD}}{T_{VP}} \quad (7)$$

$$\varepsilon_{VP}^C = \frac{1}{f - 1} \quad (8)$$

There is a possibility to use the correlation between ε_{vpiz} and ε_{vp}^C :

$$\varepsilon_{VPiz} = M^* \cdot \varepsilon_{VP}^C - N^* \quad (9)$$

In this case, the raw efficiency of the heat pump becomes:

$$\varepsilon_{VP} = \varepsilon_{VPiz} \cdot \eta_{iz} = (M^* \cdot \varepsilon_{VP}^C - N^*) \cdot \eta_{iz} \quad (10)$$

$$\varepsilon_{CD} = 1 + \varepsilon_{VPiz} \cdot \eta_{iz} = 1 + (M^* \cdot \varepsilon_{VP}^C - N^*) \cdot \eta_{iz} \quad (11)$$

Net efficiencies have the final form:

$$EER = \varepsilon_{VP} \cdot \eta_{el} = \varepsilon_{VPiz} \cdot \eta_{iz} \cdot \eta_{el} = (M^* \cdot \varepsilon_{VP}^C - N^*) \cdot \eta_{iz} \cdot \eta_{el} \quad (12)$$

$$COP = \varepsilon_{CD} \cdot \eta_{el} = (1 + \varepsilon_{VPiz} \cdot \eta_{iz}) \cdot \eta_{el} = [1 + (M^* \cdot \varepsilon_{VP}^C - N^*) \cdot \eta_{iz}] \cdot \eta_{el} \quad (13)$$

For the most used refrigerants (R410A, R134A, R407C, R507, R32), the approximate values of the coefficients M^* and N^* are given in the following table:

Table 1- Coefficients M^* , N^* , refrigerants

Refrigerant	M^*	N^*
R410A	0,958	1,5321
R134A	0,9812	1,2825
R407C	0,957	1,3453
R507	0,9642	1,8975
R32	0,9487	1,2586

In order to determine the annual EER and COP, the percentage share of the required monthly energy that is fully replenished by heat pumps must be established with the formula:

$$Pond = \frac{E_{constlunar} \cdot (100 - G_{aet})}{E_{consannual}} = \frac{E_{constlunar} \cdot (100 - G_{aet})}{\sum E_{constlunar}} \quad (14)$$

Thus, the electricity consumed by the heat pump takes the form of:

$$E_{elPClunar} = \frac{E_{conslunar} \cdot (100 - G_{aet})}{COP_{lunar}} \quad (15)$$

$$\text{and} \quad E_{elPCanual} = \sum E_{elPClunar} \quad (16)$$

2.1.3 Consumer-specific thermal balances

The heat requirement is established by making the calculation according to SR-1907-1:2014 [43]. According to [14], [16], [17], the relation between thermal balance of the building and heating installation is as follows:

$$Q = G \cdot \rho \cdot c \cdot (t_{Tur} - t_{Ret}) = k_0 \cdot S \cdot (t_{ml} - t_i) = k_0 \cdot S \cdot \Delta t_{ml} \quad (17)$$

2.2 Methodologies for the evaluation of solar panels

2.2.1 NZEB building requirements

The name *NZEB building* (nearly zero-energy buildings) was introduced into European legislation as early as 2010 [9]. The Energy Performance of Buildings Directive has set out that all new buildings comply with these requirements from 2021. In order to obtain these very low consumptions, the following measures must be taken:

- insulation of the building envelope must be very good, by means of advanced thermal insulation systems (polystyrene over 20 cm), windows with very good thermal insulation properties, reduction of thermal bridges;
- economical lighting systems, heating, ventilation installations, ensuring a significant decrease in energy consumption per square meter or year, using equipment with a high operating efficiency;
- the use of heat recovery systems;
- the use of systems using renewable resources.

In order to achieve these requirements, an energy calculation methodology has been developed that is constantly improved until the Mc001 version of 2021 [36].

2.2.2 Calculation methodology used for the energy assessment of solar panels

In this doctoral thesis, for energy determinations, the solar thermal calculation methodology was used to determine solar systems developed within the Methodology for evaluating the energy performance of buildings (Mc001 of 2021 [36], which is a revised version of Mc001 from 2006 [35]), more specifically the section on the implementation of renewable energy resources.

Due to the fact that the method is new and the calculation method includes formulas and terms found only in the literature of solar thermal specialties, it was emphasized the need to develop a practical guide to the use of the method. It is

presented in the following lines (with the calculation relationships taken from the methodology):

2.2.3 Practical guide to using the thermal solar calculation method

According to [36], the most important factor showing the influence of climate, is defined as β_{REF} and is determined with the formula:

$$\beta_{REF} = \frac{t_{i0} + t_e}{I \cdot f_s} \quad (18)$$

Where I , it is calculated using the intensity of horizontal solar radiation at a specific angle of inclination, detailed in Annexes MC001/2006 [35] and is multiplied by a factor f_s representing the hours of sunrise.

Then the solar efficiency of solar panels can be calculated with the formula:

$$\eta_{BC} = F_R^{BC} \cdot [(\alpha \cdot \tau) - k_c \cdot F_{INC} \cdot \beta_{REF}] \quad (19)$$

The relationship that determines the collecting power of solar panels is:

$$P_{CP} = S_C \cdot I \cdot \eta_{BC} \cdot f_u \quad (20)$$

And the total energy produced by solar panels in 24 hours, on a certain number (N) of days is calculated with the formula:

$$E_{CP} = P_{CP} \cdot 24 \cdot N_{zl} \quad (21)$$

The power of the consumer is given by the relationship:

$$P_{CONS} = H \cdot (t_{i0} - t_e) \quad (22)$$

For thermal analysis of the heating case, the coverage degree of the solar installation can be determined for each month with the formula:

$$G_{aet} = \frac{P_{cp}}{P_{cons}} \quad (23)$$

The efficiency of the heating system with solar panels can be determined monthly with the formula:

$$RND = \frac{P_{cp}}{P_l} \quad (24)$$

To determine the degree of annual coverage and annual efficiency of the system, it will make the average for each month of heating.

2.3 Methodologies for the evaluation of heat pumps

In order to evaluate the performance of a heat pump included in a solar system, it was chosen the option of calculating the actual efficiency of the heat pump by using the isentropic efficiency resulting from the calculation of the Carnot efficiency of the refrigeration machine [25].

To simplify the system, it can be considered that the temperature in the tank is introduced with a certain temperature which is then raised to the temperature of the heat supply by the heat pumps.

In order to provide thermal energy only from renewable resources, the heat pump is sized to the lowest monthly coverage offered by the solar panels for the system to run on thermal energy from renewable resources only. This can lead to an oversizing of the heat pump, but you can also opt for the sizing for March and add an additional classic source. The additional classic source must be provided together with a trivalent boiler, which has the coil at the top of the boiler and operating only on the coldest days of the year. This is not mandatory, this doctoral thesis did not study this specific case, because it was intended to use heating systems based solely on renewable energy resources.

2.4 Calculation methodology used for the economic assessment of system profitability

In existing or pending rules and methodologies [35] and [36], an economic calculation is described that addresses all renewable resource-based improvement solutions as a whole. It has been adapted to the application within this chapter.

The economic analysis of a new solar investment for existing buildings is carried out through the economic indicators of the investment. Of these, the most important are the following:

- the net present value of the additional investment due to the application of an energy rehabilitation/modernization project and the energy savings resulting from the implementation of the said project, $\Delta VNA_{(m)}$ (lei) ;
- the duration of the return on the additional investment due to the application of an energy rehabilitation/modernization project, N_R (years), representing the time elapsed from the moment of making the investment in the energy modernization of a building and the moment when its value is equaled by the value of the savings achieved by the implementation of energy modernization measures, brought to the initial moment of the investment;
- the cost of the saved energy unit, e [lei/kWh], representing the ratio between the value of the additional investment due to the application of an energy rehabilitation/modernization project and the energy savings achieved through its implementation during the recovery of the investment.

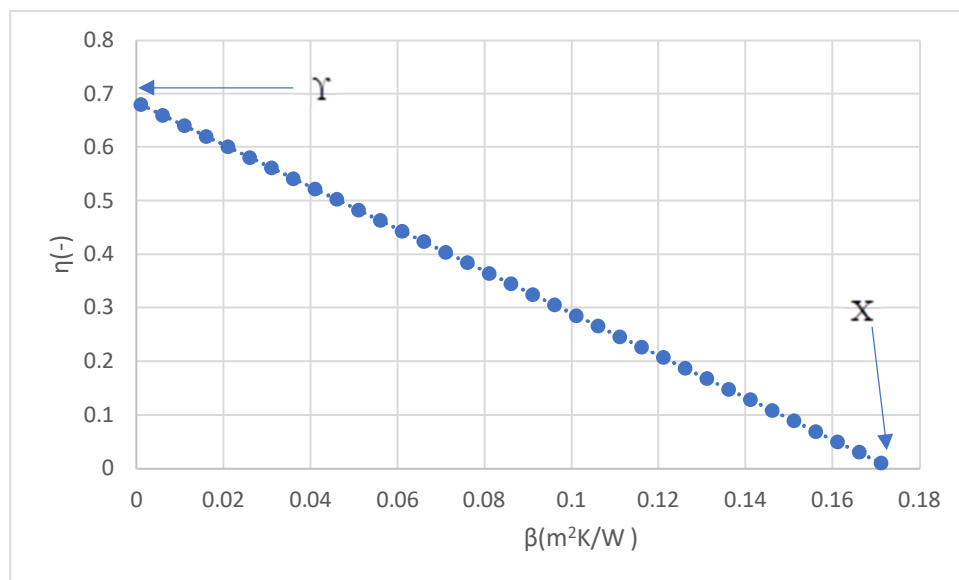
3. EXPERIMENTAL MODEL

3.1 Description of the experimental research

Having the theoretical bases from chapter 2, it was aimed to study some practical aspects that will help in completing the thermal solar calculation methodology. In the PhD thesis, participating in a national program aimed at using a solar installation, I conducted research presented in the scientific research report number 2 that focused on two main aspects:

- Establishing a linear expression of the overall coefficient of heat transfer of the solar capturer, k_c by its quadratic shape that includes the variation of the temperature in time for the capturers installed in operation;
- Determination of the thermal characteristic of the solar collector (and the optical coefficient of the panel, $\alpha\tau$) in current exploitation regime in relation to the thermal characteristic of the solar catalog capturer (optical efficiency offered by the manufacturer); the determination of the slight modification of the thermal characteristic of the solar collector in current exploitation regime is due to the alteration of the transparency coefficient of the glazed element of the solar collector.

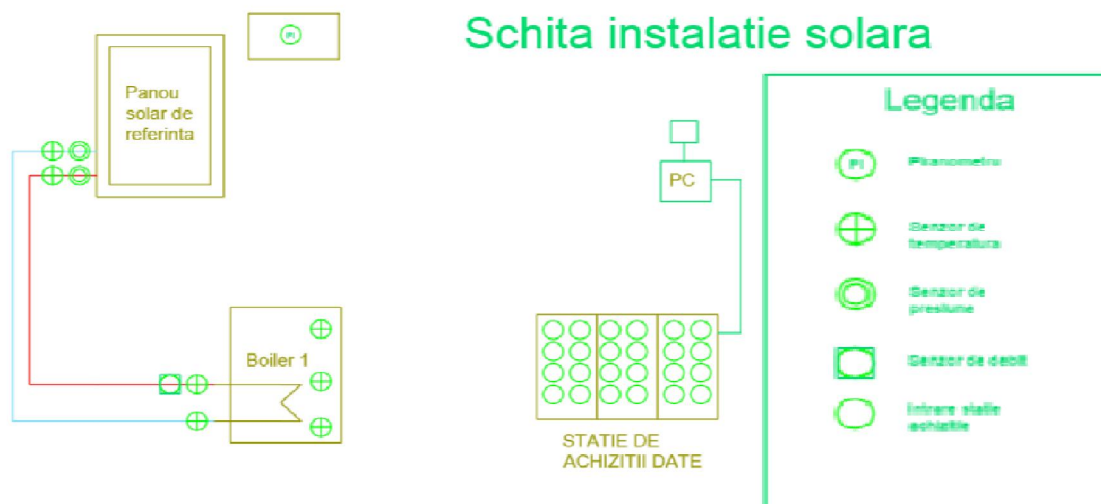
For the panel used, the following characteristic was determined, which emerged from the determination of k_c according to the β and then the integration of the optical coefficient of the panel into the equation, resulting in the operating efficiency of the solar panel:



Figură 3- Caracteristica randamentului captatorului solar în funcție de β

In [28] and [29] various corrections are made to the efficiency of the collector and its dependence is explained depending on the flow in the collector, but also on the various thermal agents conveyed through it. These papers were the basis for conducting experiments at variable flow rates.

Using the solar stand, during the experiments, values were recorded for all the sensors shown in figure 4, with a time step of 5 minutes over a period of 2 years.



Figură 4– Schema de lucru a instalației solare

3.1.1 The measuring apparatus and electronic equipment used, presentation of their representative characteristics

The system parameters that were measured during the experiment campaign are: temperature, flow in the installation, intensity of solar radiation and pressure in the installation.

For measuring the temperature inside the installation, 7 type K thermocouples with the head immersed in the fluid conveyed through the installation were used. They were inserted by perforating the copper pipes and the connection point was thermally insulated. The insertion of the thermocouples was carried out at a distance of 2 diameters from other connecting parts or clamps, in the simple copper pipe, in order to avoid the formation of thermal bridges. The outside temperature was measured with a K-type thermocouple with free head. The thermocouples were provided with a simple green insulated electric cable of variable dimensions (from 20 m to 5 m, depending on the case) which ends with a connection plug to the data acquisition device.

For measuring the flow in the installation, helical flow meters with DN 25 (FVA 915) were used, measuring from 4 l / min to 100 l / min. They operate at a maximum temperature of 85 ° C and a nominal pressure of 10 bar. Their accuracy is $\pm 5\%$. They were connected by insulated electrical cables to the purchasing system.

A spherical pyranometer was mounted to measure the intensity of the solar radiation near the solar panel. It measures the intensity of solar radiation from 0 to 1500 W / m² in the plane of the panel at an angle of 180 °. The accuracy of the pyranometer is $\pm 5\%$. The pyranometer glass must be cleaned periodically to record the correct values.

Both pressure gauges with quick-read dial and pressure sensors immersed in the circulating fluid were used to measure the pressure in the installation. The dial gauge mounted in the pump unit measures the pressure from 0 to 10 bar and the reading is done visually, helping to adjust during the experimental campaign. The

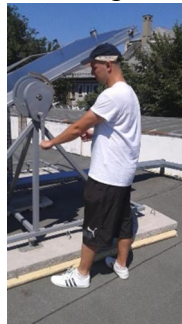
pressure sensor used (FDA 602) measures the pressure from 0 to 30 bar in liquids with a temperature between -10 and 80 ° C with errors of up to $\pm 1.5\%$.

The system parameters that were taken through a data acquisition system, within the experimentation campaign, are: temperature, flow in the installation, intensity of solar radiation and pressure in the installation.

3.1.2 - Detailing the conditions met in the experimental research

Within the experimental data collection program, the following aspects were followed:

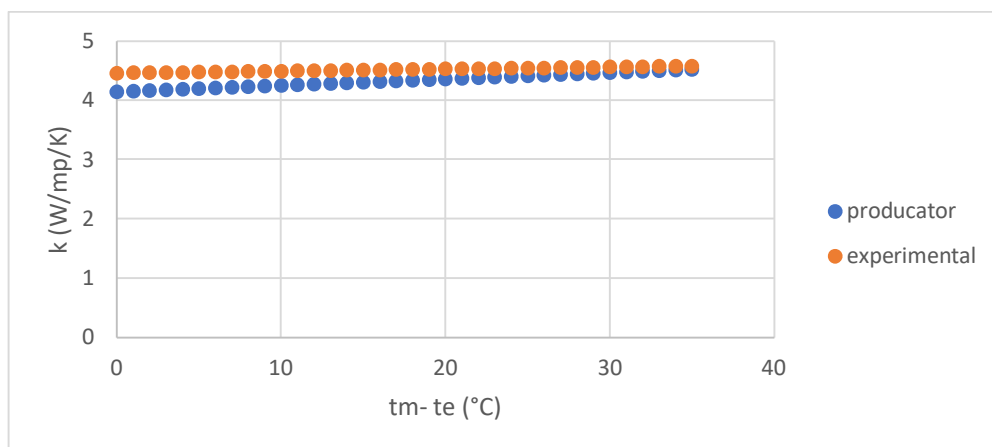
- Data collection over a transition period and a summer period;
- Setting the system to different operating flows and obtaining data;
- Data collection in different operating modes (charging, consuming, mixed);
- Establishing a program for measuring and sampling data;
- Data processing and obtaining the thermal balance on each equipment;
- Setting the panel to different angles.



Figură 5– Setting the panel to a horizontal angle

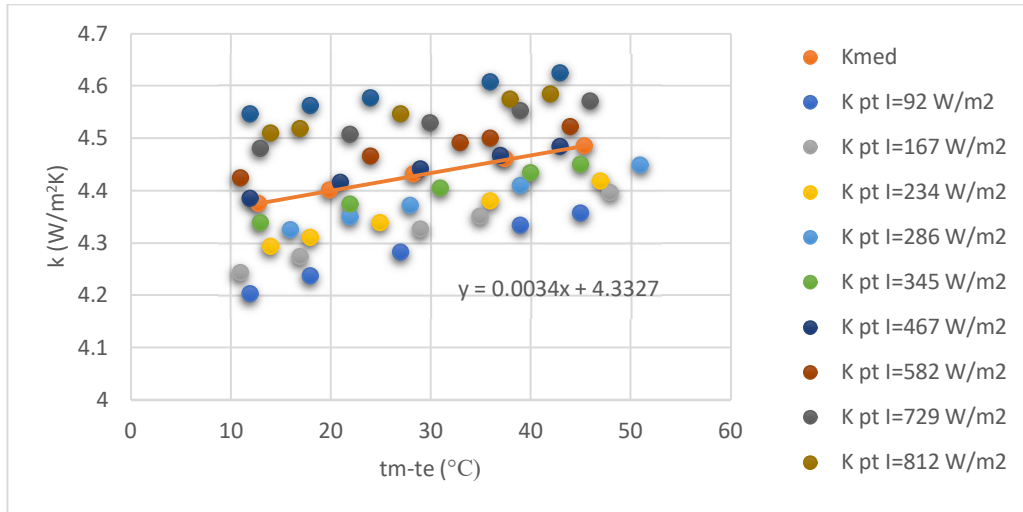
3.2 Experimental results

In these experiments, on the reference days, with a constant sunshine throughout the day, it was primarily desired to express the efficiency of the solar collector through a square shape presented in the previous chapter. This was compared with the efficiency provided by the manufacturer (Figure 6). This validated the experimental campaign.



Figură 6– Graph with comparison of the thermal characteristic of the solar panel

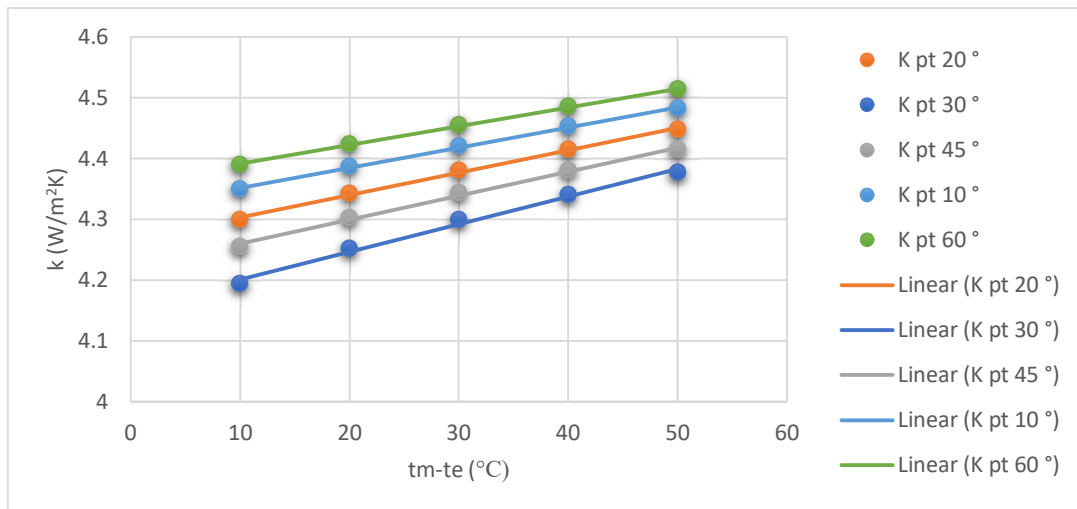
To determine this characteristic of the solar collector, in the experiments were measured: a , t_{tur} , t_{ret} , t_e and I and were approximated according to the data provided by the manufacturer α , τ and F' . Thus, the coefficients k of the collector were determined according to $t_m - t_e$ (Figure 7) and β , by two coefficients k_1 and k_2 .



Figură 7–Graph with k_c at various I values, according to experiments

The solar panel manufacturer provides the values of $k_1 = 4.14$ and $k_2 = 0.0108$ to describe the panel efficiency curve. Following the experiments, a graph was built with this curve for certain hourly average values obtained only on the reference days. Thus, certain average values of I were obtained, compared to which certain average values of k (consisting of k_1 and k_2) were assigned. Thus, values of $k_1 = 4.3327$ and $k_2 = 0.0034$ were reached for a panel inclination of 30° and a maximum flow (over $90 l / m^2h$). These values resulted in a slightly lower performance than that given by the manufacturer.

When using different orientations of the panel from the horizontal surface (10° , 20° , 30° , 45° and 60°) the values obtained for k were best at an angle of 30° (Figure 8).



Figură 8– Graph with the global heat transfer coefficient for different orientations

4. ENERGETIC PROCEDURE OF PRACTICAL APPLICATION

4.1 Construction of an energy procedure with easy and practical applicability for determining the intermediate factors in the solar methodology

From Chapter 2 and the experimental study in Chapter 3, it was concluded that a simplified form of determining the solar calculation can be obtained from the Mc001/2021 methodology [36]. In order to get to this simplified procedure, it was necessary to use the formulas in the methodology for case studies aimed at analyzing the behavior of each term in the formulas presented in Chapter 2.

4.1.1 Stages prior to the construction of the energy procedure

Thus, in order to reach the optimal construction variant of the simple and efficient calculation model, which improves the information in the methodology [36], in 2019 various intermediate researches were carried out.

Thus, it was considered a consumer, representing 80 apartments that form a residential building. For the H calculation of this building, the following scenario was performed (with calculation hypotheses):

- Each apartment accommodates an average of 2.5 people;
- Each person has a consumption of 72 l of hot water per day;
- The result is an average consumption of 180 l / day for each apartment;
- Which determines a $H_{acm} = 689 \text{ W / K}$ for the whole building;
- $H_{inc} = 16000 \text{ W / K}$ was determined by estimating a thermal heating requirement; for each apartment corresponding to a $Q = 7000 \text{ W}$.

A heat exchange system has been provided for this heating system for the primary circuit of solar panels with boiler. It is characterized by a $k_s = 600 \text{ W / m}^2\text{K}$ and the accumulation volume was introduced in the form of a ratio, dependent to the capture surface, $V_a = V / S_C = 50 \text{ l / m}^2$.

In order to obtain conclusive results at country level, 79 cities were chosen for which monthly / annual calculations were performed. Due to the fact that in Romania there was only a small database for the climatic values of temperatures and intensities of solar radiation, it was necessary to build a database. These were determined by the calculation relationships (25) and (26).

$$t_0 = \frac{\frac{1}{d_1} \cdot t_1 + \frac{1}{d_2} \cdot t_2 + \frac{1}{d_3} \cdot t_3}{\frac{1}{d_1} + \frac{1}{d_2} + \frac{1}{d_3}} \text{ [}^\circ\text{C]} \quad (25)$$

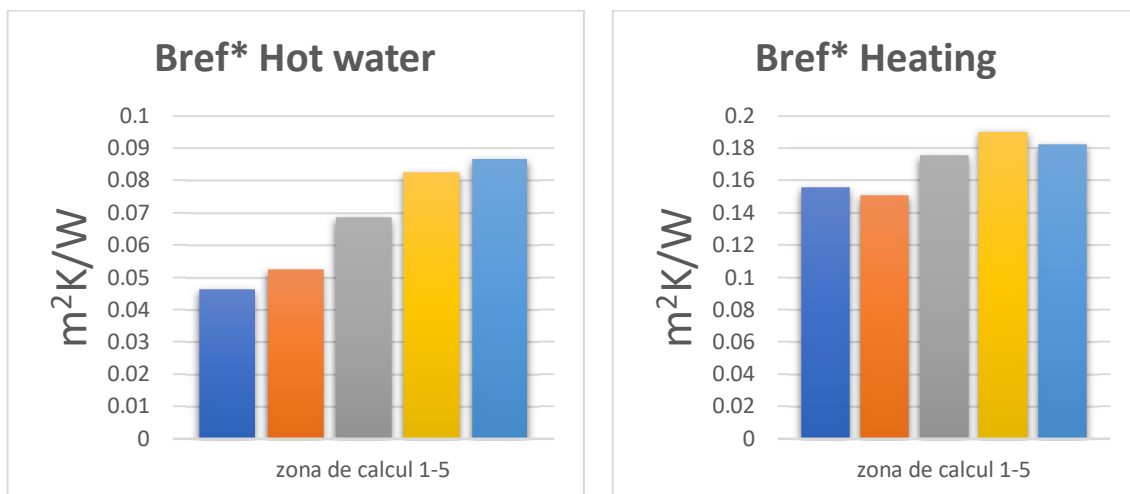
$$I_0 = \frac{\frac{1}{d_1} \cdot I_1 + \frac{1}{d_2} \cdot I_2 + \frac{1}{d_3} \cdot I_3}{\frac{1}{d_1} + \frac{1}{d_2} + \frac{1}{d_3}} \text{ [W/m}^2\text{]} \quad (26)$$

This form of representation of the characteristic of the solar system using the steps in the methodology, from Figure 10 has a shape similar to that of the solar collector, the whole system has a similar efficiency to that of the solar collector. The diagram in figure 10 is similar to the representation of the thermal characteristic of the sensor in the experimental chapter (Figure 3), managing to represent the efficiency of the sensor depending on the climatic data. This is particularly important because this graph can calculate RND and G_{AET} depending on the outside temperature and the average intensity of thermal radiation, which the previous study shows that are the two parameters that influence the solar calculation according to the methodology used.

In Figure 11, it is observed that the value of the capture yield is below 1. This is due to the fact that it is determined by two subunit factors, F_R^{BC} and optical efficiency ($\alpha\tau$). As can be seen in this figure, the maximum value that η_{BC} can reach is given by the product between F_R^{BC} and the optical efficiency of the solar panel. And this characteristic of the operation of the solar panel system was observed and discussed in the chapter of experimental research, where it was observed that this theoretical maximum η_{BC} is almost impossible to achieve under operating conditions.

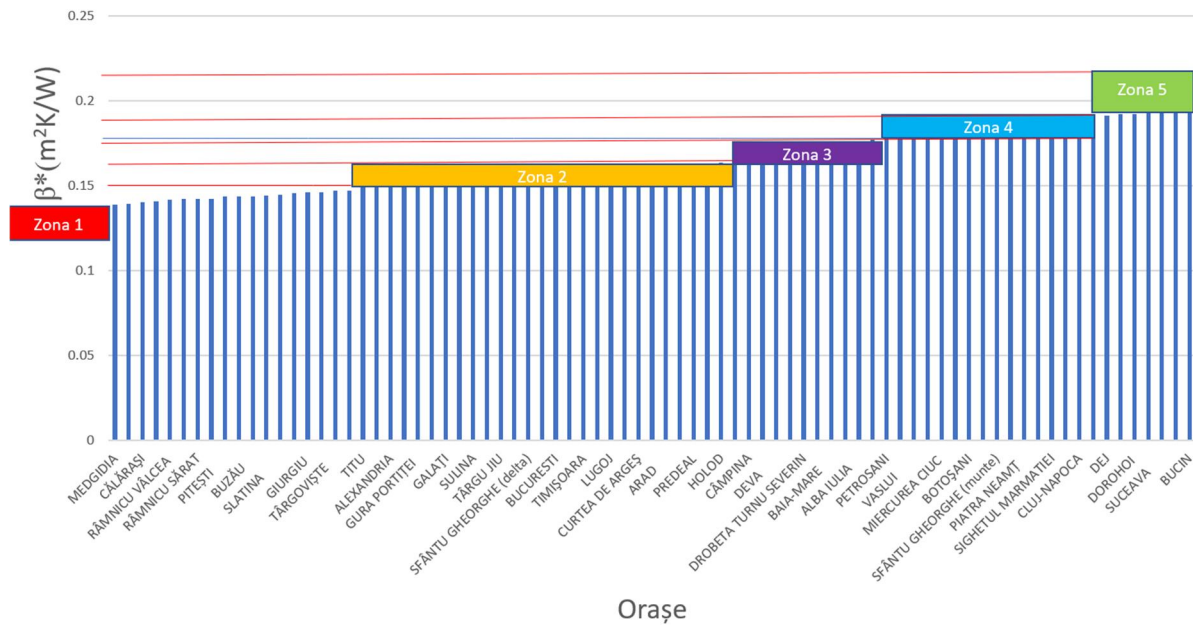
As the example from [14] was followed in the experimental part and the intersections with the axes were established, in figure 10, it is observed that for their determination, F_R^{BC} , k_c and $\alpha\tau$ must be determined. This central calculation diagram shows the main factors to be determined, in addition to these being listed, also F_{inc} , which can be seen from the formula η_{BC} . For this, T_{tur0} , T_{ret0} and the solar collector area must be established.

Due to the fact that climate calculation areas have been designed for air conditioning calculations and take into account only the external calculation temperature, the β_{REF} indicator is much more comprehensive for solar applications. To determine these calculation areas, all 79 localities for which the previous determinations were made were used. If both β_{REF}^* are calculated for the 79 cities and the climatic zones are used for heating, we obtain:



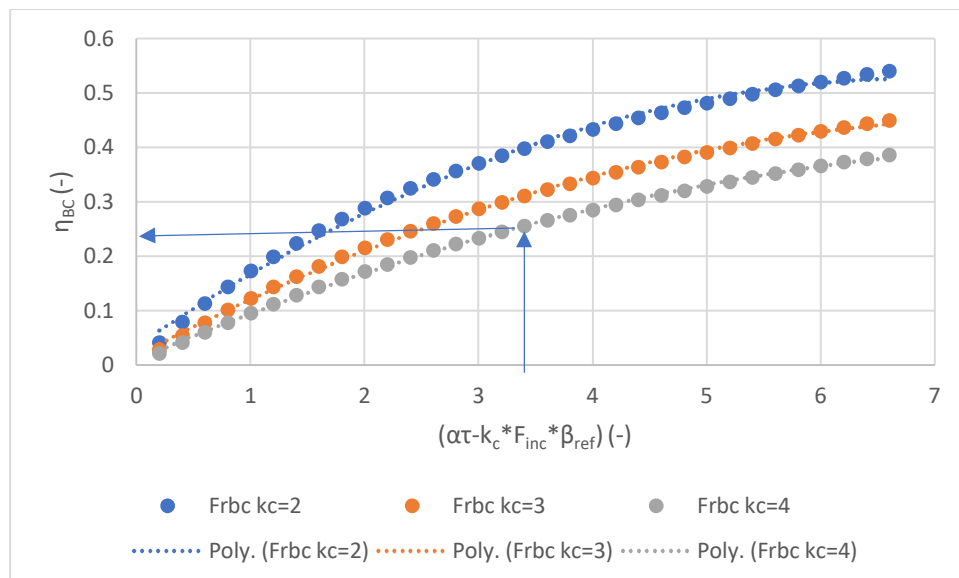
Figură 11 a,b- Presenting the factor β_{REF}^* for each "classic" climatic zone

To facilitate the calculations, it is possible to choose a zonal environment β_{REF}^* or you can read from the graph its specific value for the city closest to the chosen objective. This value will be entered later in the nomograms. Thus, the climate indicator β_{ref}^* is determined by entering the city in the figure:



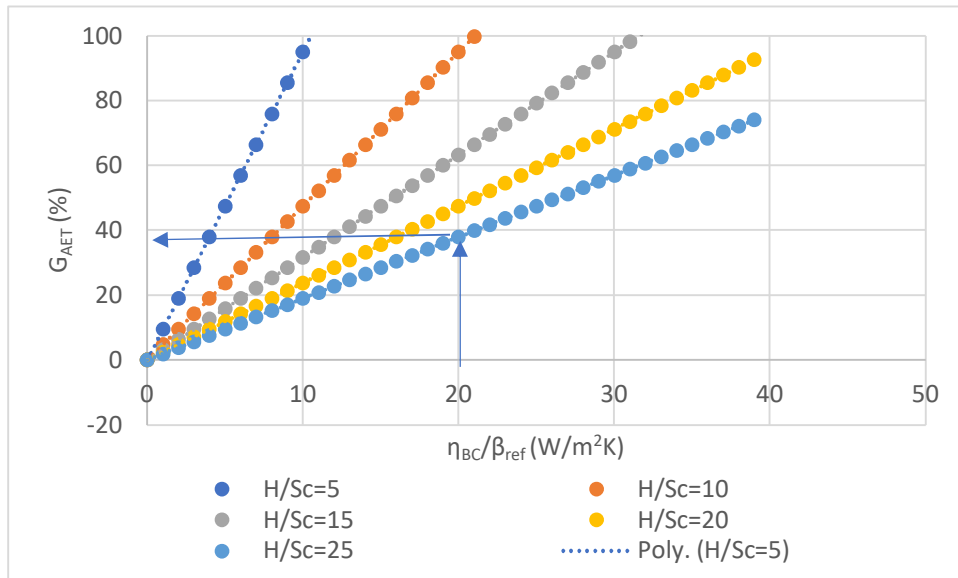
Figură 12- β_{ref}^* annually for heating case calculation areas

You can calculate the capture efficiency of solar panels by choosing the type of panel used, both for the heating case shown in Figure 13:



Figură 13- Calculation diagram for η_{BC} heating

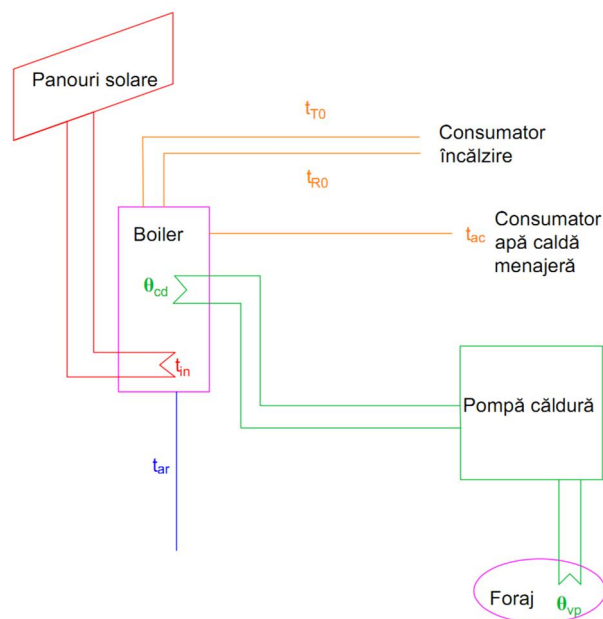
Then G_{aet} is calculated for the heating case, depending on the chosen H / S_c ratio (after choosing the use factor) and entering in figure 14 with the value of the η_{BC} / β_{inc} ratio known from the other graphics presented in the thesis:



Figură 14- Calculation diagram for G_{aet}

4.1.3 Romania's characteristic energy procedure for heat pumps

The monthly energy consumption for the heating and domestic hot water preparation situation is supplemented by a second heat pump system that produces heat energy to meet the needs of the consumer. It uses a mechanically compressed heat pump that uses R410A refrigerant. The heat pump has the condenser in the tank and the evaporator in a drilled well. In the thesis, the heat pump is characterized by an electricity consumption and a monthly COP for the cold season. This was dimensioned for the most unfavorable calculation month.



Figură 15- Calculation scheme of heat pumps

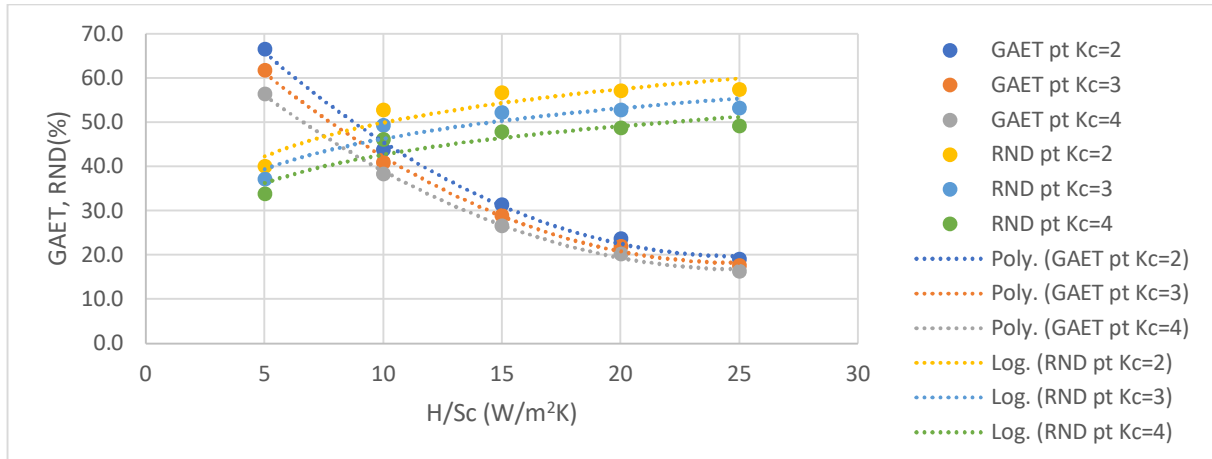
To calculate these terms, the carnot cycle must be established, which results in isentropic efficiency and then results in effective efficiency. It all starts with the temperature values of the hot (well temperature) and cold (temperature in the storage tank) environment. Thus the temperature of the cold environment (in which it is desired to introduce heat) determines the condensation temperature. By integrating the equipment (heat pumps) into the system used so far, the solar panels manage to heat the water in the storage tank to a certain temperature that can be estimated using the degree of thermal coverage. For the calculation of this internal temperature of the tank, in the case of heating, t_{in} , the formula is used:

$$t_{in} = t_{R0} + (t_{T0} - t_{R0}) \cdot (G_{aet}/100) \quad (27)$$

4.2 Results of the application of the energy procedure

4.2.1 Results of the energy procedure for solar panels

To complete the analysis according to the capture efficiency at country level, the influence on the most important energy performance indicator for solar panels, energy coverage (G_{AET}), the variation of the two parameters analyzed above, the type of collectors is to be determined. solar and the size of the catchment area. This study was carried out for each of the five solar calculation zones characteristic of Romania, for example for zone 1, for the case of supply of thermal agent for heating at temperatures 50/30 °C:



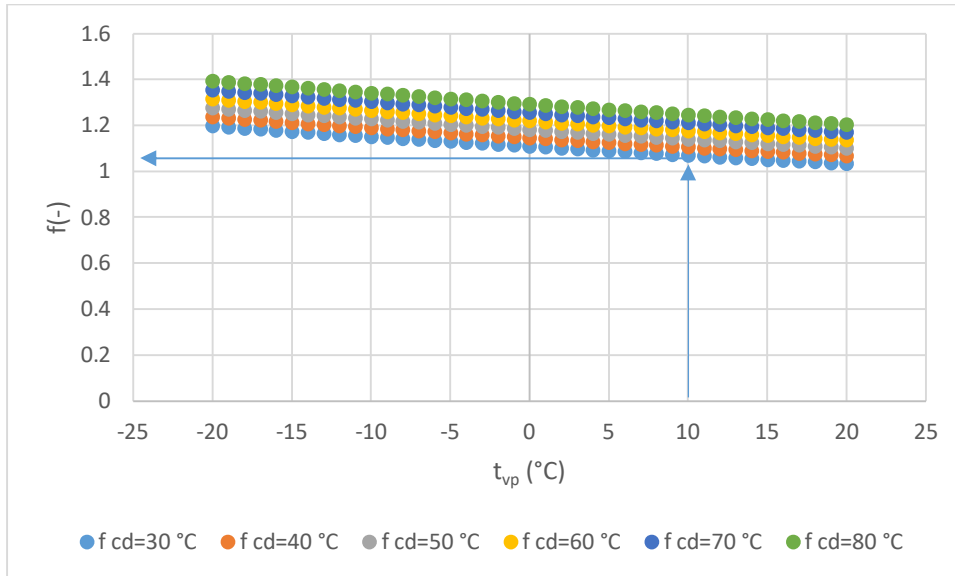
Figură 16- Coverage levels and capture efficiency for heating, solar zone 1

4.2.2 Results of the energy procedure for heat pumps

Using a water-to-water heat pump that extracts heat from a well drilled to the depth of the groundwater, it is used as a simplifying hypothesis $t_{vp} = 10$ °C, being approximately constant throughout the year. Condensation temperature is the average between the flow temperature and the temperature in the tank that was previously calculated.

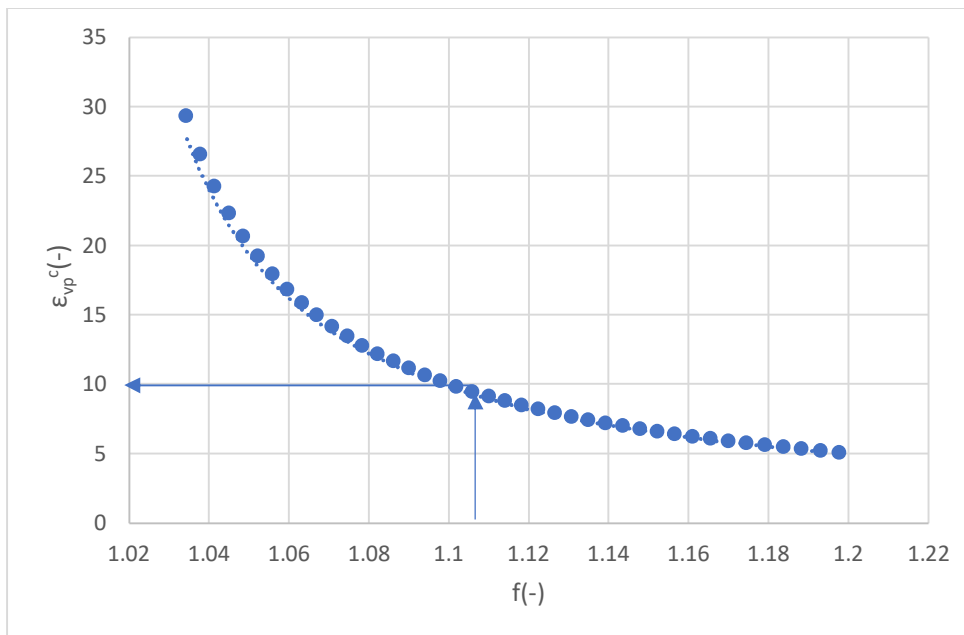
In this case, using the calculation method described in chapter 4.1.3, a range of values for the ratio $f = T_{CD} / T_{VP}$ can be determined using the heat pumps for the most favorable case (solar panels with $k_c = 2$, $H / S_c = 5$ and $t_{tur} / t_{ret} = 50/30$ °C for solar

calculation zone 1 and the most unfavorable case (solar panels with $k_c = 4$, $H / S_c = 25$ and $t_{tur} / t_{ret} = 90/70$ ° C for solar zone 5 of solar calculation), the other possible values being placed in this field, respectively, 1.11 ... 1.16. Thus, we can calculate f according to t_{cd} and t_{vp} , after their transformation into Kelvin from °C:



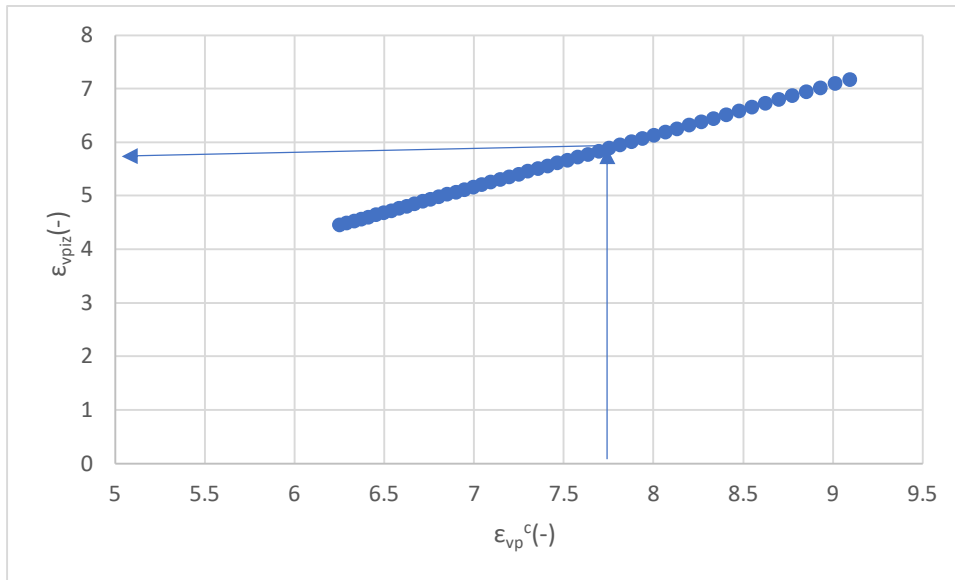
Figură 17- Isentropic efficiency (ε_{vpi}) depending on f

Thus, the variation of isentropic efficiency can be shown $\varepsilon_{vpiz} = M^* \cdot \varepsilon_{vp}^c - N^*$ depending on $\varepsilon_{vp}^c = \frac{1}{f-1}$ (figura 19) which depends on this factor f , established a range of values (figure 18):



Figură 18- Carnot efficiency ε_{vp}^c depending on f

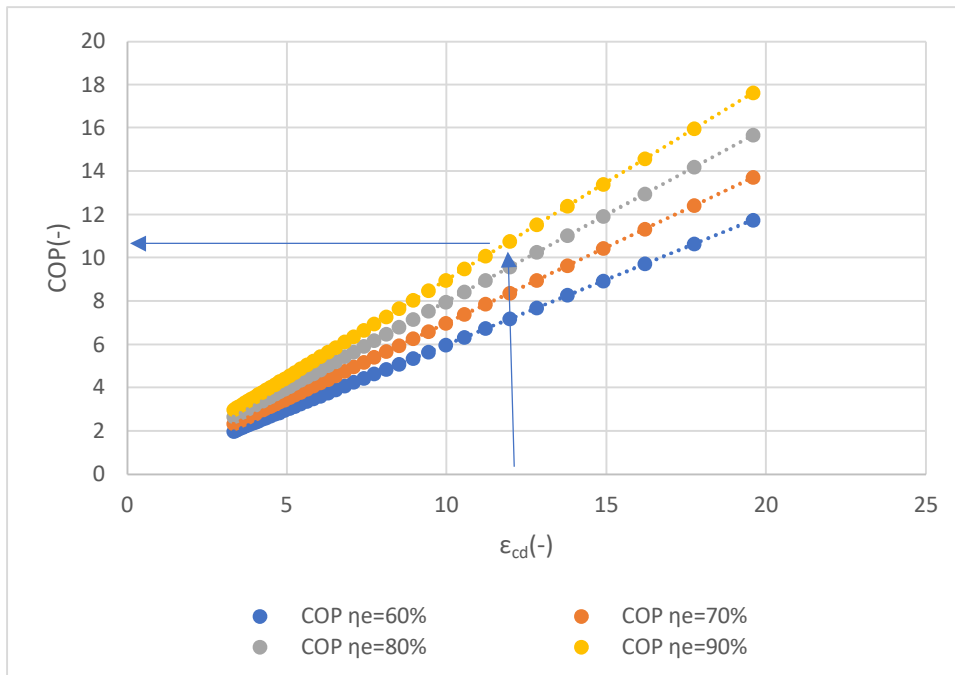
Figure 19, using the coefficients M^* and N^* from Table 1, shows isentropic efficiency as a function of carnot efficiency:



Figură 19- Isentropic efficiency (ϵ_{vpi}) as a function of ϵ_{vp}^c

It is observed that the isentropic efficiency increases with the Carnot efficiency of the refrigeration machine, being directly proportional to this and to the COP of the heat pump.

In order to calculate the COP of the heat pump, depending on the condensation efficiency obtained, the graph in Figure 20 was made:



Figură 20- COP as function of ϵ_{cd}

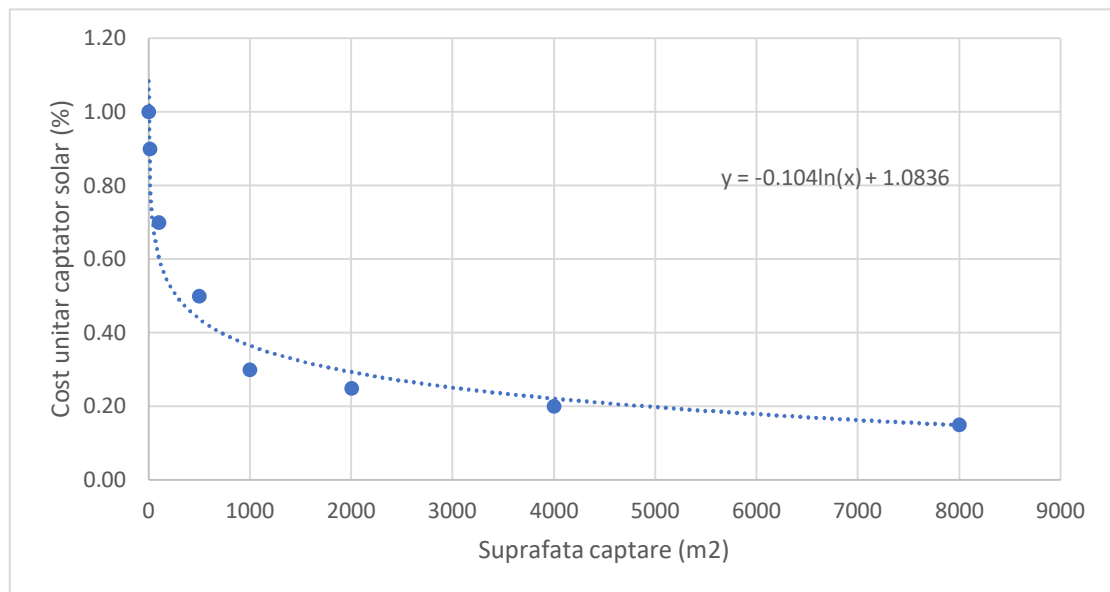
5. ECONOMIC CALCULATION PROCEDURE

5.1 Construction of the economic procedure

In order to justify the investment in this system that uses energies from renewable resources, an economic analysis adapted to the energy cases obtained in Chapter 4 was performed, based on some of the formulas from the MC001 calculation methodology.

5.1.1 Stages prior to the construction of the system's economic procedure

In 2019, within the doctoral thesis, an economic calculation was made that approximated an initial investment cost that depends nonlinearly on the collector area. Due to the fact that the price per piece of a solar panel depends on the number of panels purchased, the real situation is simulated by a price reduction depending on the solar collector area shown in Figure 21.

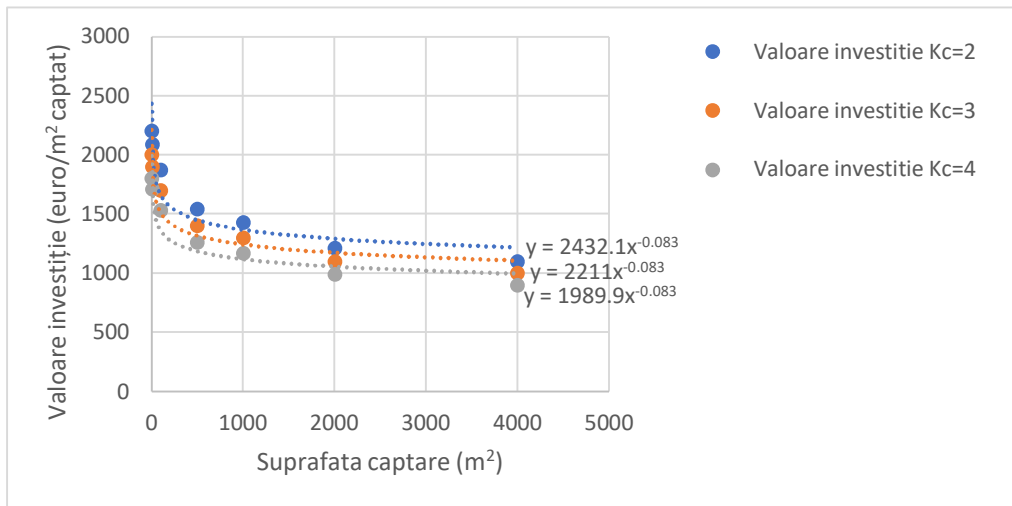


Figură 21- Dependence of the unit price of a solar panel on the number of panels purchased

The initial investment costs per piece for the three types of panels corresponding to $k_c = 2, 3$ and 4 were the following: 3000, 2000 and 1500 euros (corresponding to the purchase of a single product). These include both the cost of the solar panel and the assembly work for the panel (which is fixed, representing 800 euros for each panel and included in the total amount presented above). The chosen prices are average prices chosen for the Romanian market at the time of initiating the study. The estimated lifespan of the solar installation is 20 years. Maintenance and upkeep costs were neglected in this calculation, being insignificant in relation to the value of the investment. This investment cost was updated with an inflation rate of 7% and a growth rate of 7%. Thus, the Net Present Value of the investment was obtained. The latest RADET tariff plan was used to calculate the price per MWh. The conversion into euros at the BNR exchange rate was carried out and thus a price of 126 euros for 1 MWh was obtained. This tariff was multiplied by the annual value of usable energy produced by the solar system and the annual value of heat savings was obtained.

5.1.2 Economical calculation procedure for solar panels

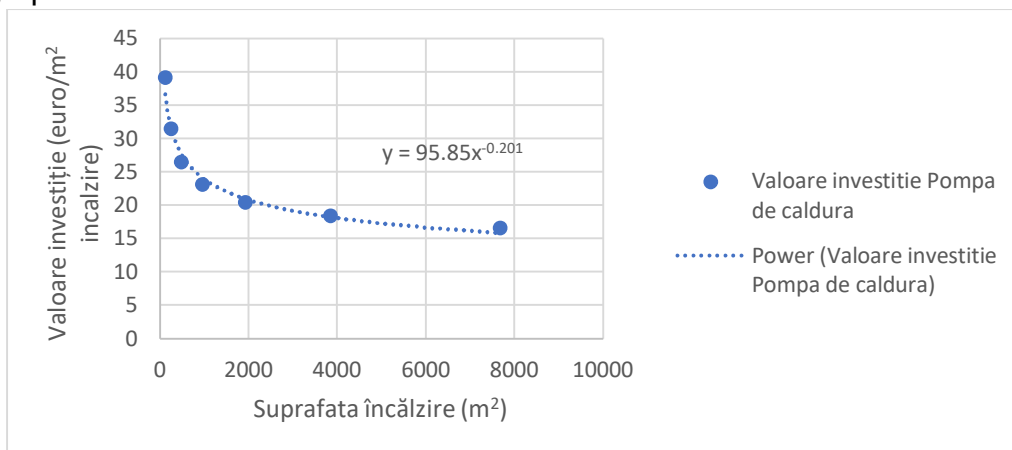
The calculation model has been improved and updated with energy tariffs and prices in 2021 (because in 2021 there were reductions in the solar panel market). Thus, the reduction coefficient included in Figure 21 was integrated in the equation corresponding to each type of solar collector (with a k_c of 2, 3 and 4) resulting in the economic graph that expresses the value of the investment according to the capture area:



Figură 22- The reduction of the investment value with the increase of the acquired catchment area

5.1.3 Economical calculation procedure for heat pumps

When constructing the model for the economic calculation of heat pumps, the investment cost for heat pumps was determined following the economic graph of heat pumps with vertical drilling chosen (Figure 23). This cost included the cost of the heat pump, geothermal drilling, additional coil for the water tank and additional connections in the technical room. Thus, this investment cost was determined using the formula in the graph:

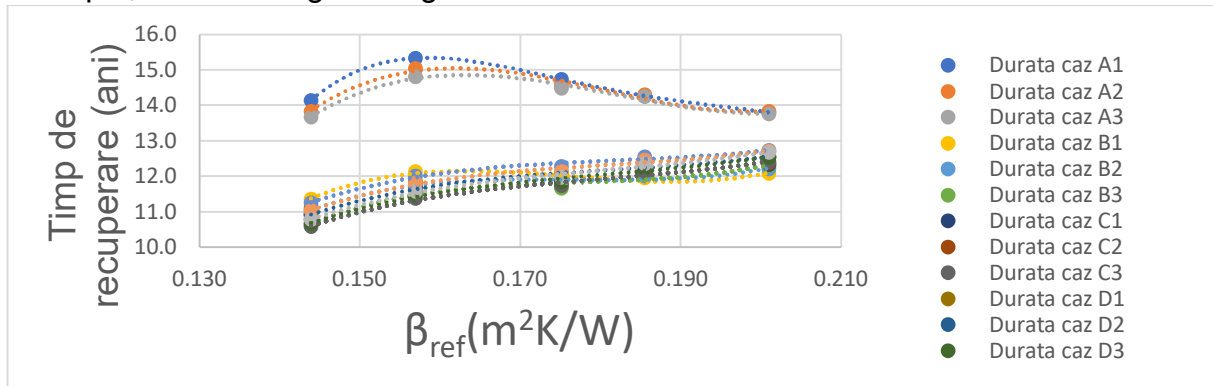


Figură 23- The reduction of the investment value with the increase of the heating surface provided by the PC

5.2 Results obtained by applying the economic procedure

5.2.1 Results obtained by applying the economic procedure for solar panels

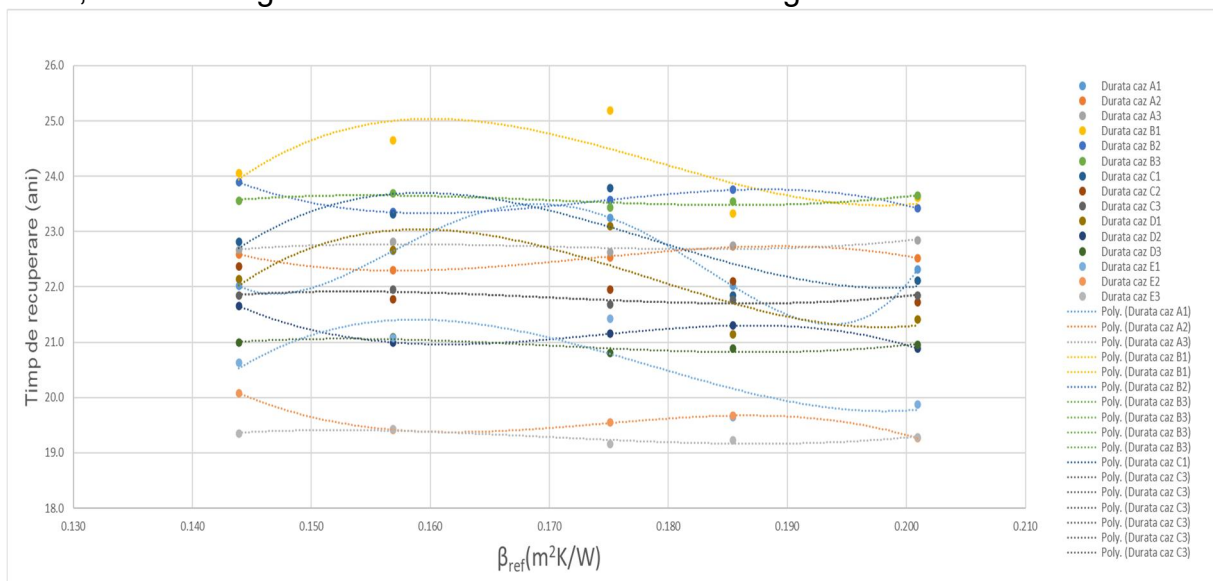
Using the economic model described in Chapter 5.1, several cases were calculated to represent the best option to invest exclusively in solar panels. For example, the following heating case results were obtained:



Figură 24- Economic graph with solar panel recovery time, heating case at $t_{T0} / t_{R0} = 50/30$ °C

5.2.2 Results obtained by applying the economic procedure for heat pumps

Due to the fact that part of the energy is produced by the solar panels and part by the heat pumps, through the chosen cases it was wanted to highlight which percentages corresponding to each installation are better to prepare the thermal agent. Thus, the following results were obtained for the heating case:



Figură 25- Economic graph with recovery time of the complete installation, heating case at $t_{T0} / t_{R0} = 50/30$ °C

6. CONCLUSIONS, PERSPECTIVES AND PERSONAL CONTRIBUTIONS

6.1 Conclusions

Within the doctoral thesis, the research obtained from the research reports were integrated which aimed at: documentary studies on the chosen topic, experimental and theoretical studies to fulfill the purpose of the thesis, to achieve a practical and easy to understand nature of the solar methodology and adapt the system so that it includes heat pumps.

In the experimental study, there was a difference in capture efficiency depending on the system on which it is integrated (consumer) by the manufacturer. This operating characteristic differs due to the operating mode of the panel pump and whose influence is described above. Given that the solar panel was tested in real conditions, with regular maintenance, but which allowed the study of real conditions of use that led to the reduction of optical factors, using an anti-freeze thermal agent and a start and stop program of the pumps, the solar collector had lower performance than those obtained by the manufacturer in ideal (laboratory) conditions. The experiments performed fulfilled their goal of testing a solar panel in real test conditions. The thermal characteristics for the solar collector were determined, a stratification of the temperatures in the boiler was observed and a consumption represented by a heat pump was simulated by which the thermal load was discharged and its operation was observed.

The identical results obtained from the research validate the new calculation method in case of using identical calculation principles (the same monthly average), having the advantage of simplifying the existing method. By changing the average hourly calculation intensity, new possibilities are generated to evaluate the real hourly efficiency of solar installations. Thus, it can be seen that although the real hourly efficiency of the installation increases during the year, the hourly efficiency of the system that includes the heating needs of the consumer decreases due to the limitation of the hourly thermal energy required. These conclusions provide a new insight into how solar systems are treated and suggest certain 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 (larger storage tank) or by introducing higher control temperatures (by means of automations) during this solar charging regime.

The energy study concludes that there may be solar configurations that generate a thermal energy saving required for heating residential buildings of about 30-40% nationwide in the case of easy installation of these systems in most homes. This value is considerable and can lead to a greater energy independence of Romania. For the preparation of hot water, solar panel systems can fully provide the necessary thermal energy, being more efficient and having less restrictive conditions than in the case of heating.

6.2 Perspectives and recommendations

The efficiency of these systems can be improved by control units that make a consumption forecast and intelligently use the discharge and loading cycles of the storage tank.

The performance of the solar collector was slightly weaker than that given by the manufacturer and due to the fact that the azimuth of the panel had a different value of 0. It is recommended to follow the orientation given by the manufacturer in the data sheets, but in real conditions it can almost never be perfect for the cardinal points.

The optimal value of the inclination of the panel may differ from that obtained by 30 ° depending on the period of use of the year. It is recommended to use values of this variable angle throughout the year. This can be done by accessing the panel and integrating a support that allows this. The values of 45 ° are recommended during the transition period, and those of 60 ° for the winter period. Mobile support requires a minimal investment that results in a considerable improvement of over 10-20% of the sensor's performance (as shown in the experimental study).

6.3 Personal contributions

Within the doctoral thesis, an energetic and economic method with a practical and easy to understand character applied to the existing methodology of thermal solar from MC 001/2021 was developed, which develops and particularizes the calculation relations from this methodology. Through experimental studies, a linear expression of the global heat transfer coefficient of the solar collector, k_c was established and a slight alteration of the thermal characteristic of the solar collector in current operation was observed, finding its cause in altering the transparency coefficient of the glazed element. This led to the introduction of a 5% reduction in the value of the optical output declared by the manufacturer for a higher accuracy of the calculations in MC 001/2021. Following the experiments, the operating characteristic of the solar panel was determined and it was compared with the operating characteristic of the system, according to the methodology, finding the connection between them.

The doctoral thesis identified the set of parameters that must be controlled to obtain energy results that express the performance of solar collectors in terms of heating homes and domestic hot water preparation. These are:

- k_c - global heat transfer coefficient of solar collectors, W / m^2K ;
- $H / (k_c S_c)$ - the dimensionless ratio between the transmittance of the building and the indicators of the solar collector area;
- T_{tur} / T_{retur} or T_{ac} - thermal control temperatures, ° C.

The influence of the variation of these performance indicators for the solar panels was shown and the optimal values for them were determined, corresponding to Romania on the basis of which the determinations were performed. The thermal regulation temperatures, the solar coverage ratio (H / S_c) and the type of solar collector

(k_c) also varied, so that the studies lead to the generation of the data necessary to make a solar map for our country. A calculation solar climate indicator (β_{ref}) and optimized (β_{ref}^*) were determined for the energetic and economic determination of the systems that are composed of solar panels and new solar climate calculation zones were introduced. These solar climate zones have contributed to the introduction of a new graphical calculation method with great practical ease, and the solar performance can be approximated only by evaluating the graph corresponding to the solar climate zone in which the locality is included.

The calculation formulas from the existing energy methodology have been simplified and new simplified calculation formulas have been obtained for the most common cases of systems in Romania consisting of solar panels and heat pumps, the designers obtaining directly the degrees of solar coverage, the efficiencies capture, heat pump electricity.

A new calculation procedure was introduced in addition to the solar calculation from MC001 / 2021, using calculation diagrams and obtaining with a high degree of accuracy the degree of solar coverage and the efficiency of the solar installation. This method can be used for any calculation configuration, and for the calculation of heat pumps certain specific cases have been introduced that help to choose a solar and heat pump configuration, doing all the energy calculations in just a few seconds. The grapho-analytical method for solar panels is very easy to use, you enter a certain value in each graph, obtaining a value for the next graph, thus reaching the final result consisting of G_{aet} . In this way, the design and rapid determination of the energy feasibility of these systems has been considerably facilitated.

By introducing the calculation graphs within the additional energy procedure, the possibility was created to directly choose the type of solar panel and heat pump used, by comparing it with other possibilities that lead to other energy results. For heat pumps, a grapho-analytical method was designed in which a value is entered in a series of graphs, reaching step by step the final result, which consists in finding the COP of the heat pump and then at determination of the electricity consumed by the heat pump.

A specific economic calculation procedure has been designed, customized for solar panels and heat pumps, having the foundations in MC001 / 2021, but specifically addressing these systems and facilitating calculations by introducing new formulas and introducing the possibility of obtaining results only in graphical form. The economic efficiency of a system that uses exclusively renewable energies was shown and the possibilities of its optimization were shown, intelligently choosing the production ratio between solar panels and heat pumps. Economic graphics have been drawn up indicating the best ratio of solar panels / heat pumps. An economic analysis was performed that completes the energy analysis at the country level and indicates the return on investment and the specific cost for most cities in Romania, located in all regions of the country that can be used to assess the profitability of these systems. This analysis directly allows developers to choose a predetermined case and obtain an estimate of the return on investment.

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