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Procedura simplificata de evaluare a sistemelor fotovoltaice

Simplified PV panels system energy evaluation procedure

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Rezumat: Lucrarea prezentată reprezintă o metodologie simplificată de evaluare a sistemului fotovoltaic în ceea ce privește energia generată, acoperirea globală a cererii de energie a sistemului analizat, energia suplimentară necesară din rețea și performanțele sistemului la modificarea parametrilor de montaj. Ecuații propuse și legătura cu metodologia națională MC001 și anexele acesteia, lucrarea propune o evaluare rapidă a aspectelor economice și a perioadei de rambursare. S-a demonstrat că investițiile în astfel de sisteme sunt rambursate rapid în perioade de la 4 până la 5 ani pentru consumatorul obișnuit cu un consum mediu zilnic de 11,15 kWh. În ultima parte a procedurii, a fost definit un parametru de suprafață specific consumatorului, util în calculul rapid a suprafeței solare nete totale a sistemului pentru a satisface un consumator cunoscut. În final, a fost studiată locația Bucureștiului, iar parametrii propuși de ecuațiile date au fost supuși unei evaluări de optimizare.

Cuvinte cheie: Energie regenerabilă, panou fotovoltaic, MC001, SEN

Abstract: Presented paper represent a simplified methodology for evaluation of PV system with regards to generated energy, overall energy demand coverage of the system analyzed, supplementary energy required from the grid and performances of the system when mechanical parameters are changed. Proposed equations and link with Romanian national methodology MC001 and its annexes the paper proposes a quick evaluation for economic aspects and refund period. Was shown that investments in such systems are rapidly reimbursed in periods of 4 to 5 years for common household appliances consumer with a daily average consumption of 11.15kWh. In last part of the procedure, it was defined a specific consumer specific surface parameter, useful in rapid return of system total net solar surface to satisfy a known consumer. In the end, location of Bucharest was studied, and the parameters proposed by this paper equations where subjected to an optimization evaluation.

Keywords: Renewable energy, PV panel, MC001, SEN

1. Introduction

The use of PV panels system for residential building electrical energy demand is more and more an adopted solution of customers to household energy bills increase. Solar radiation is a constant waveform that heats the Earth. The PV panels technologies known a wide development in terms of transforming surface materials or increased efficiency.

Due to their easy installation and low exploitation costs, usage of such technology is only an energy balance question, with focus on overall cost reduction and electrical energy generation. To evaluate such systems, a simplified procedure is the best approach when decision of implementation required an easy approximation of yearly energy coverage of a specific consumer energy. Not being so simple to distinguish an average energy demanded in residential sector for example, a specific evaluation per unit of kWh consumed, may be a good choice when the daily or monthly energy consumption is known or can be approximated based on several previous months consumption. This paper will propose several energy and qualitative parameters together with their specific equations to reflect the impact of several PV panels geographical position installation based on known specific horizontal solar irradiation from national normative.

2. Methodology description

The method described below evaluates overall electrical energy obtained by PV panels systems, in monthly intervals, for one year.

First step is to evaluate a PV panel system using the methodology described in MC001. In the methodology, horizontal solar radiation is presented as daily average for each month of the year and for several Romanian cities. The same methodology presents a set of correction factors, depending on azimuth and tilt angle of PV panels, to calculate the corresponding tilt radiation shown by equation 1.1.

$$I_{tilt} = I_{T,Oriz} \cdot c_c \qquad 1.1.$$

In Standard Test Conditions, PV panels efficiency is evaluated based on the maximum power, $P_{max,1000}$ obtained on its surface when the PV panel is tested with equivalent tilt surface equal 1000W/m^2. Based on net solar PV panel surface A_{pan}, representing the net area that will transform the radiation on electrical energy without the case and boundary frame of it and with Standard Test Condition radiation can be expressed efficiency. This efficiency is calculated with maximum power presented in PV panel datasheet with equation 1.2 or can be given as a specific parameter by some of PV panel manufacturers. In both cases, efficiency represents same indicator and can be used with same meaning during evaluation. This efficiency is a separate indicator of solar PV panels depending on each manufacturer and materials used in production. In worm environments, PV panels functionality depends on external conditions, such the air temperature, their thermal efficiency being a known parameter that harms overall energy production (η_t).

$$\varepsilon_{PV} = \frac{P_{max,1000}}{A_{pan} \cdot I_{1000}} \qquad 1.2$$

PV panels electrical energy is produced in DC type due to semiconductor material characteristics with junction based that allowed to circulate only the current in one direction from its Anode to Cathode when photons from solar radiation affect the electron- hole pairs. DC current produced cannot be used in residential building were household appliances, TV and all types of electrical devices work with AC type current. To commute from DC to AC current, inverters are used. Those devices use the technique of switching the DC poles with a frequency of 50-60HZ and thus creating an alternate current useful in residential electrical energy applications. Being electronical devices inverters introduce their own efficiency (η_{inv}) in the system.

For a specific system with several installed PV panels, the monthly energy it is expressed as sum of all daily energy produced. Using the tables from the MC001 methodology, correction coefficient from Annex A1 based on azimuth and tilt angles, and thermal efficiency, some examples can be found in Annex A2, monthly electrical energy obtained by the system is calculated with equation 1.3 were index i represents the month number in the year for which the evaluation is performed.

$$E_{l,i} = \frac{1}{1000} \cdot 24 \cdot N_{zl} \cdot A_{tot} \cdot I_{tilt} \cdot \eta_{t,i} \cdot \eta_{inv} \cdot \varepsilon_{PV} \qquad 1.3$$

$$E_{tot} = \sum_{1}^{12} E_{l,i} \qquad 1.4$$

Total energy produced by the system is easily found as the sum of all monthly energies obtained over the year, given by equation 1.4 were Nzl is month days number.

3. Procedure steps frame

The evaluation procedure frame consists in several useful steps to determine each parameter, calculate the specific efficiency, and evaluate overall energy produced by the PV panel systems. Firstly, are assessed PV panel system components such total net solar surface, tilt and azimuth angles and inverter type and its efficiency. After this step can be evaluated corresponding horizontal solar radiation for the location where system is installed based on charts in MC001. Third step is selection of right correction coefficient, based on physical characteristics found at first step, from Annex A1 and PV panel thermal efficiency from Annex A2. Finally, the total energy produced is calculated as the sum of all monthly energies. Bellow a frame of the steps is presented.

First step:

a. Count and note the number of PV panels, Np;
b. Measure and note the tilt angle of PV panels as the angle with horizontal line;

c. Measure and note azimuth angle, as the angle that surface of PV panels and South imaginary line forms.

d. Extract from the datasheet the maximum power of PV panel for Standard Test Conditions;

e. Calculate the efficiency in case the maximum power in Standard test Condition is presented inside datasheet;

f. If efficiency of PV panel is given by manufacturer, use it and ignore steps d and e;

g. Extract from datasheet the equivalent net surface of PV panel;

h. Search the inverter efficiency on its case as a declared parameter or found it on manufacturer datasheet.

Second step:

i. Select from Annex A1 the corresponding correction coefficient;

j. Select the corresponding table with horizontal solar radiation from MC001, annex A.9.6 based on location;

k. Calculate total surface of all PV panels;

l. Calculate tilt solar radiation using equation 1.1;

m. Calculate PV panel efficiency using equation 1.2 or select it from datasheet;

n. Calculate and memorize all monthly electrical energy using equation 1.3;

o. Sum all of energies using equation 1.4 and find the overall energy obtained.

Using data of systems and following the procedure steps frame the evaluation of PV panels system is an easy task, data presented in MC001 helps the designers of such systems to answer the energy demands of the final consumer.

4. Application example:

Following procedure steps frame from chapter 3, it was evaluated a system described by components in table 1.

Table 1

Ui	45	[º]
Ua	0	[º]
Np	9	[-]
$P_{max,\ 1000}$	375	[W]
Location	Bucharest	[-]
η_{inv}	0.96	[-]
Apan	1.92	[m^2]

System proposed for application example is composed by nine PV panels with 1.92 m^2 net solar surface each. Tilt angle is 45° and the azimuth angle is 0° which represent its orientation towards South. Inverter which makes the conversion from DC current produced by PV panels to AC current used by household electrical devices has a good efficiency of 0.96. Total net surface counts 17.28 m^2 and equivalent efficiency calculated by equation 1.2 is 0.195. Thermal efficiency is 0.8 during hot period of the year, with 0.85 for transition periods in spring and autumn and 0.9 on cold period. Monthly thermal efficiency can be seen in table 2. Maximum PV panel power is 375 W obtained from the manufacturer datasheet.

Table 2

	Jan.	Feb.	Mar.	Apr.	Mai.	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
η_t	0.9	0.9	0.85	0.8	0.8	0.8	0.8	0.8	0.8	0.85	0.9	0.9

Corresponding values of correction coefficient were selected from Annex A1 of MC001 methodology as can be seen in table 3.

Table 3

	Jan.	Feb.	Mar.	Apr.	Mai.	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
c_c	1.76	1.45	1.25	1.05	0.94	0.88	0.90	1.03	1.22	1.45	1.62	1.67

For Bucharest, horizontal solar radiation and corresponding corrected tilt radiation are presented on figure 1 as an average hourly solar radiation on each month during the year.

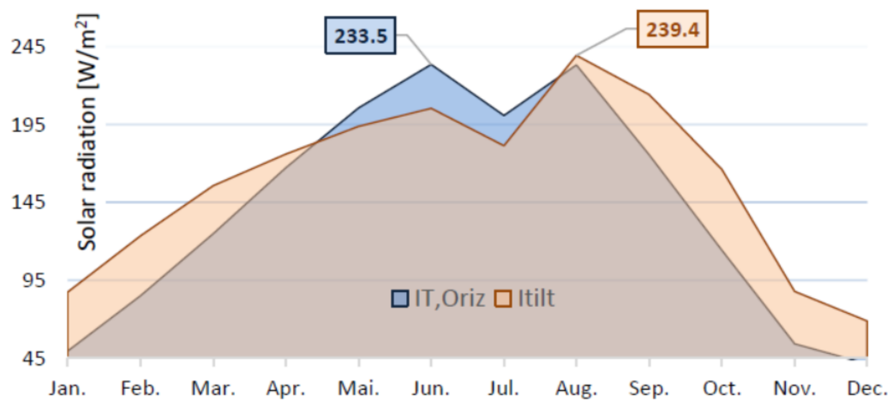

Figure 1

Solar radiation on horizontal and tilt surface are plotted as surfaces with their maximum values marked in bold for each corresponding type inside the flags with same colors. Can be easily observed that corrected tilt radiation based on tilt angle is increased comparing with horizontal solar radiation during cold periods, the 45º values bringing an advantage in the system. Despite period between May and July when corrected solar radiation is below horizontal radiation values, the overall obtained energy is higher than demanded energy, shown further in the paper, for the mentioned period of the year. Therefore, the best angle of tilted surface is a key parameter to respond to optimization question always asked in PV panel system design.

Using equation 1.3 monthly electrical energies are calculated, results being plotted in figure 2. Values represent the total electrical energy generated by the PV panels system during each month of functionality.

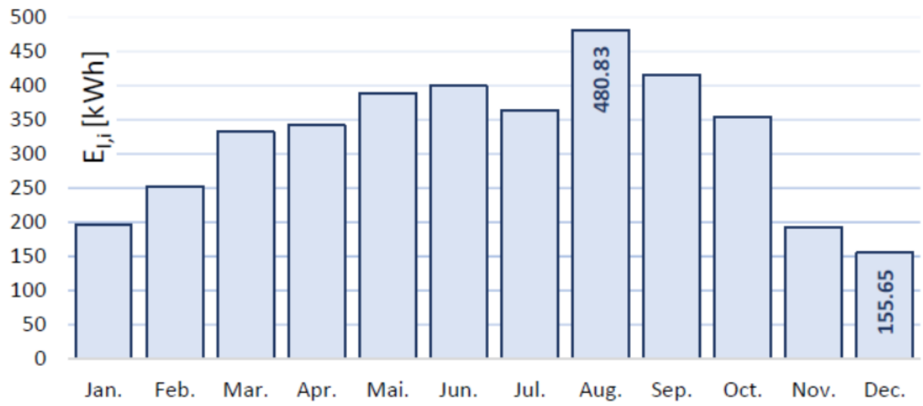

Figure 2

For Bucharest, the location studied by this example, the maximum generated energy was obtained during August when the system can generate approximatively 480 kWh with all 9 PV panels representing ±890Wh per day from each squared meter of PV panels system surface and a corresponding minimum generated energy of ±290.5Wh/m^2 each day in December.

For a given specific consumption of a residential consumer can be evaluated the overall energy balance between demanded and generated energy from the solar system. Thereby, using an average consumption, by equation 1.5 can be evaluated monthly electrical energy demand.

$$C_{m,i} = N_{zl,i} \cdot E_{d,d} \qquad 1.5$$

Inverter ON grid technology used in European Union give the advantage of discharging the additional energy generated by the PV panels in the grid, when there is more than demanded available energy that can be produced in system. This energy can be used by other customers of same Electrical power companies connected to same power grid system. Thus, the energy surplus is introduced in National Electrical Energy System (SEN) not being lost when consumer don't use it. A simple calculation between generated energy and demanded energy can be done using equation 1.6, its results being positive when is extracted energy from the grid respectively negative when PV panel solar system produce energy in excess and discharge it inside grid.

$$E_{SEN,i} = C_{m,i} - E_{l,i} \qquad 1.6$$

For the example of this application, a consumer with average electrical energy demand of 11.15kWh per day, and using equations 1.5 and 1.6, figure 3 is plotted with each energy corresponding values.

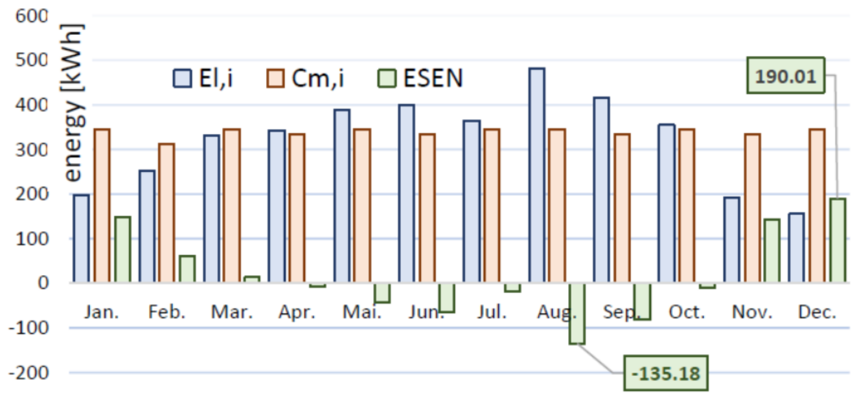

Figure 3

Figure 3 shows in one graph all 3 specific energies that characterize the functionality of system composed by PV panels, consumer, and Energy grid. Green labels show maximum energy injected in the grid in August and extracted from the grid during the cold month with low solar radiation in December. PV panel system has the capacity to satisfy consumer demand in 8 months during the year, even that as a plus it will inject energy in the grid for same period making such systems being relevant for residential application in which electrical energy from renewables is requested as primary type of electrical energy used.

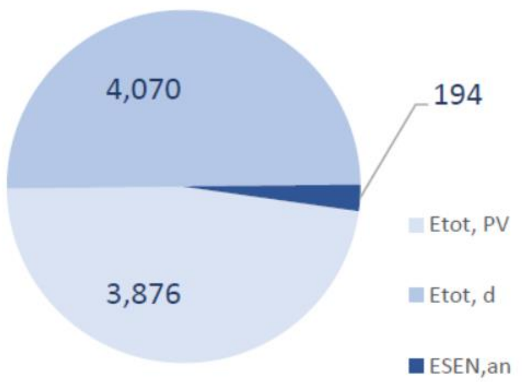

Figure 4

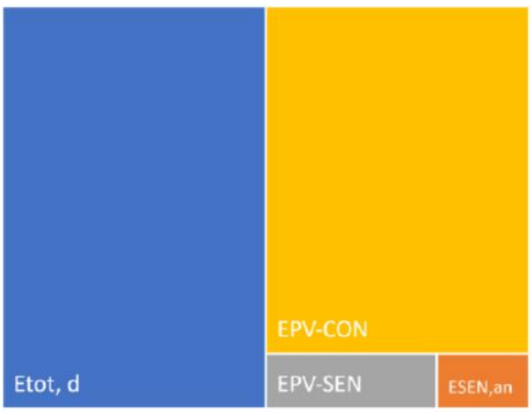

Figure 5

During the year, total energy demanded by the consumer, and total energy injected in the grid by the system, are evaluated with equation 1.7 respectively 1.8. Over the year, PV panel generated energy is directly used by the household electrical devices and appliances named PV to consumer energy symbolized EPV-CON, but in same time can be injected on National Electrical Energy System named bellow PV to SEN energy and noted EPV-SEN. PV to consumer energy and PV to SEN energy are both evaluated with equations 1.9 respectively 1.10

$$E_{tot,d} = \sum_1^{12} C_{m,i} \quad 1.7$$

$$E_{tot,SEN} = \sum_1^{12} E_{SEN,i} \quad 1.8$$

$$E_{PV-CON} = E_{tot,PV} - E_{PV-SEN} \quad 1.9$$

$$E_{PV-SEN} = \sum abs\left(E_{SEN,i}\right)\Big|_{E_{SEN,i}<0} \quad 1.10$$

Total energies and their distribution are shown in figure 4. Values are expressed in kWh with 4070 kWh total energy demanded over the year. From this value, 3876 is generated with PV panels system and only 194 is required from National Electrical Energy System, representing 4.77% from the total demanded.

Energy injected in SEN is the sum of absolute values of all monthly negative energies representing the flow from PV panel system to National grid. In figure 5 the blue rectangle represents total demanded energy over the year with distributed energies from PV and supplementary energy extracted from the grid. PV to SEN energy is symbolized with grey rectangle and represent the energy that is sent to the grid but, when required, is extracted from the grid, over the months when PV panel system cannot generate the total demanded energy.

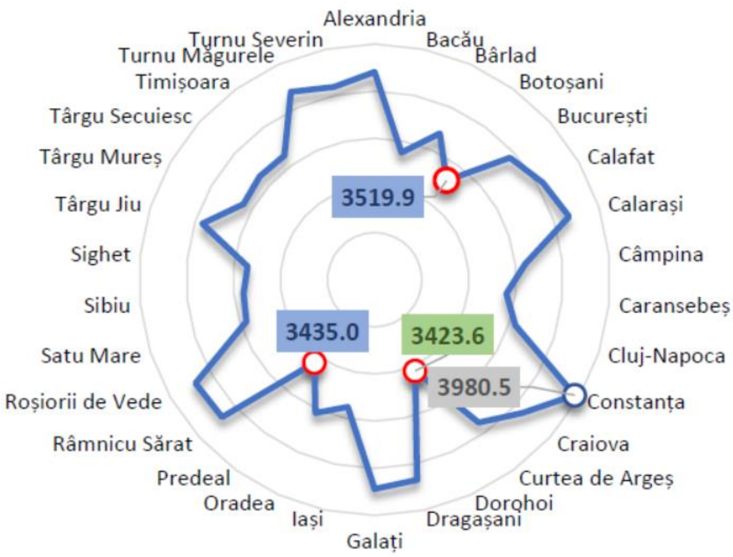

Figure 6

The analyze was extended to other 29 cities of Romania, which cover major of different specific climate over its territory. Romania consists in 5 distinct climatic zones, as described in Methodology MC001, with warm environment over the year in South-East coast area near Black Sea till the coldest zone in the Middle Carpathian area, where temperatures can degrease bellow -25ºC. In figure 6 can be observed generated energy of the PV panel system for all 30 cities in same configuration as previously example.

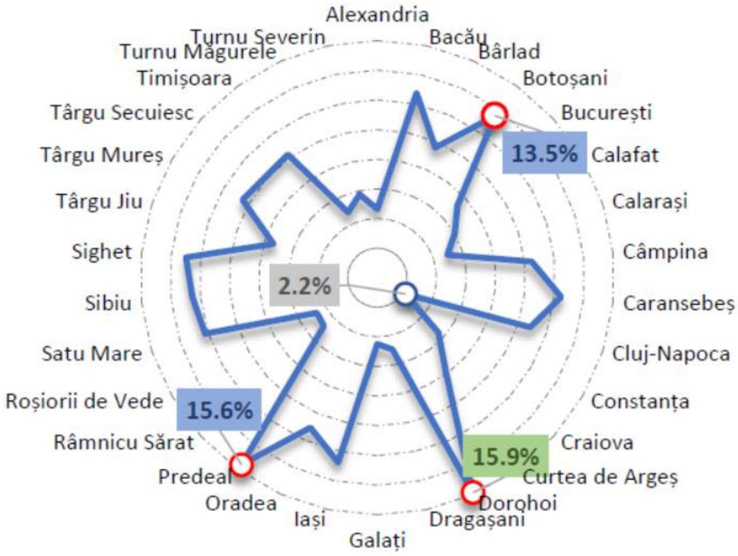

Figure 7

Due to warm climate and higher solar radiation, in Constanta, a city located on the Black Sea coast, the total generated energy of 4980,5 kWh with the biggest benefits for the same system. As can be seen in Figure 7, the percent of required energy from the field ESEN, Constanta offer the best location of all 30 where only 2,2% of supplementary energy is required from the grid. The situation is opposite for 3 cities like Predeal, Dorohoi and Botoșani, marked in red circle on Figure 7.

A short economical analyze was done for all the cities to evaluate the recovery period of the investment in such a system, based on prices of electrical energy as the drawback parameter. Therefore, the investment is refund with the total generated energy over the year. The annual economy consists of EPV-CON energy which will not be paid anymore by the consumer. Both energy and tax prices being a refund cost per kWh of generated energy as can be seen on equation 1.11.

$$p_{ref,year} = E_{PV-CON} * (p_{kWh} + p_{tax}) \qquad 1.11$$

Table 4

Pv panel nb	PV panel	Inverter	Installation	Battery	Total Investment
9	1200	5500	5000	4004	25304.32

The refund period is evaluated with number of years necessary for the investment to be paid by the annual economy. In Figure 8 are presented the results for all cities evaluated in terms of refund period where the initial investment consists in all components prices according to table 4, prices being shown in RON.

Chart from figure 8 shows the refund period, in years, for all 30 cities. With Constanta on the lowest investment recovery period all the other cities are not too far from it. The most disadvantaged city Dorohoi, need approximatively half of year more to refund all the investment.

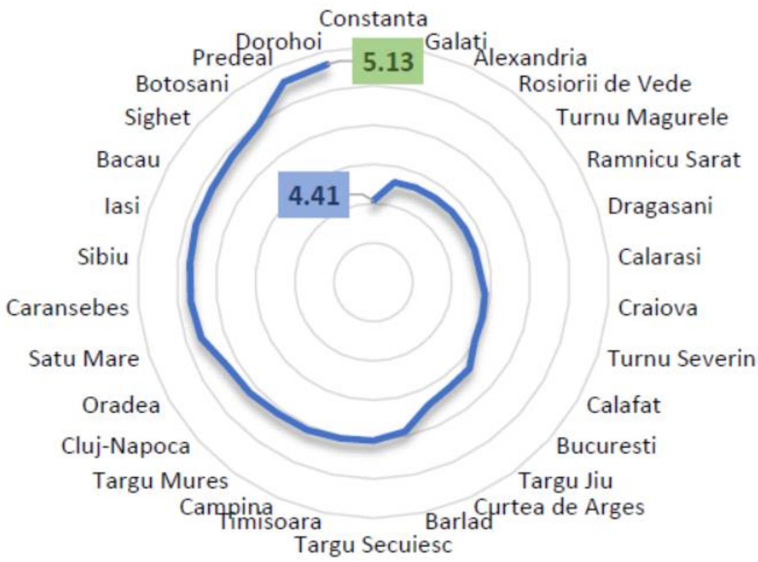

Figure 8

The question on the table of PV panel system designer is what system is needed to satisfy the consumer. For a specific energy demand this question can be resolved by a numerical evaluation based on What-If Analysis commonly used nowadays.

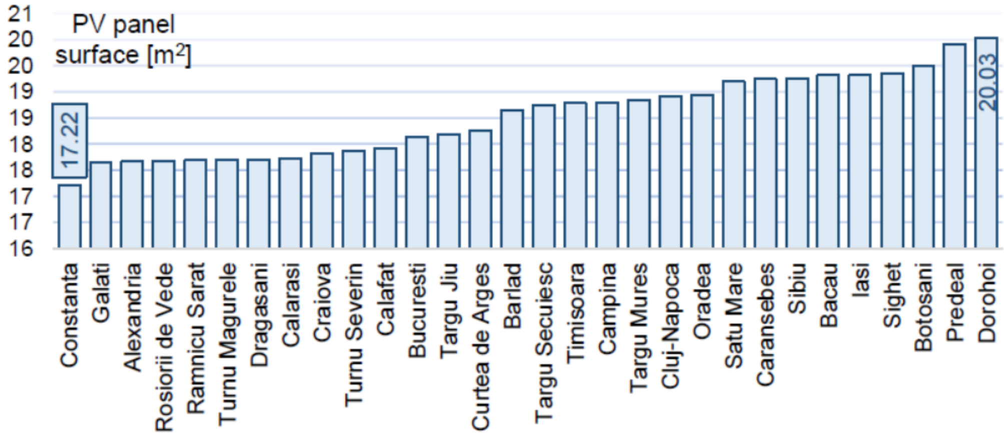

Figure 9

Goal-seek is useful for such approach, just by request of what is the total net surface of PV panels to satisfy the total demand of energy over the year. Using equation 1.3 and 1.4 with the error is established by difference between demanded energy $E_{tot,d}$, and annual PV Panel solar energy generation $E_{tot,PV}$. With a difference of 16.3% towards Constanta, Dorohoi required 4.81m^2 more PV panel surface to satisfy annual energy demanded by consumer. In figure 9 can be observed all cities necessary surface for the system to generate the entire energy necessary by the consumer.

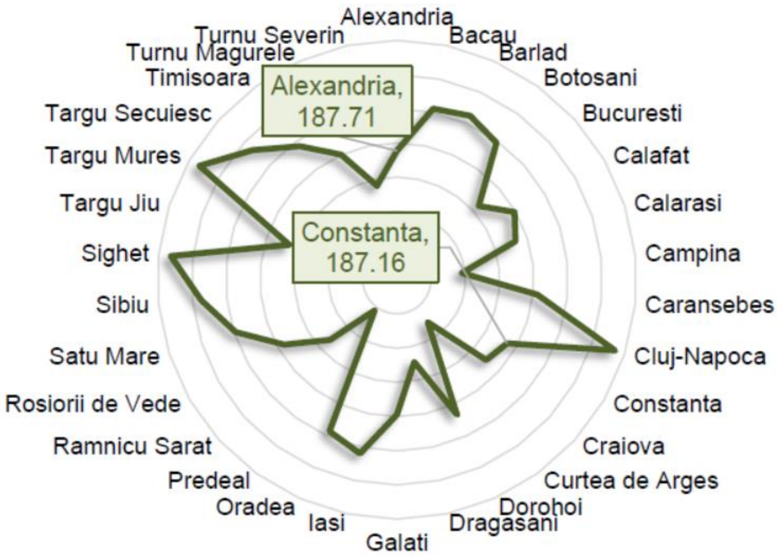

Figure 10

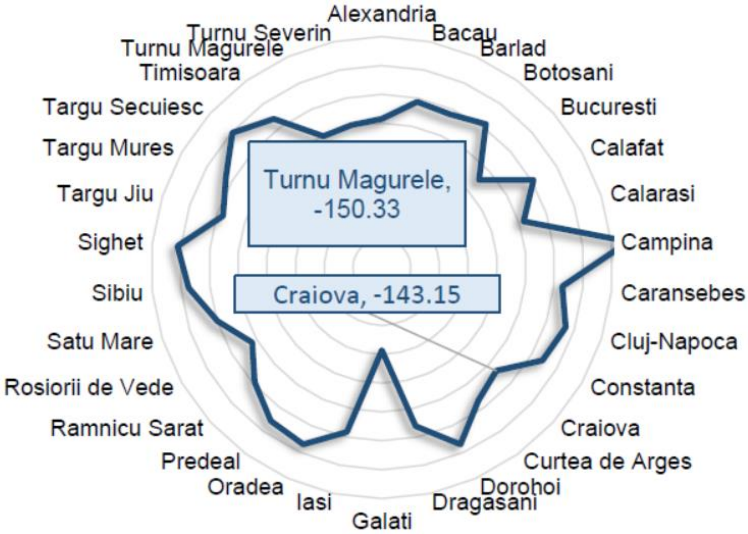

Figura 11

In figure 10 can be observed the maximum supplementary energy, ESEN, required for each location in the worst month solar radiation conditions. Predeal and Curtea de Arges requests maximum of supplementary energy from the grid even the overall energy obtained from PV panel system is sufficient for consumer demand. The total energy extracted from the grid will be delivered during the year back into SEN when solar radiance will be higher. In the same analyze data, where studied the values of maximum injected energy in the grid, plotted in figure 11. Negative values symbolize the flow of the energy from PV panel system towards the grid. Even in Constanta the solar radiation is at its maximum on studied locations, the maximum injected energy is obtained at Galati. This is possible by the group “solar radiation” – “total PV panel surface”. Because Galati required 0.4m^2 more surface, and different solar radiation, during August the total energy delivered in the grid, 192.67, is higher comparing with value from July in Constanta where is injected 121.4kWh in the grid, at its maximum.

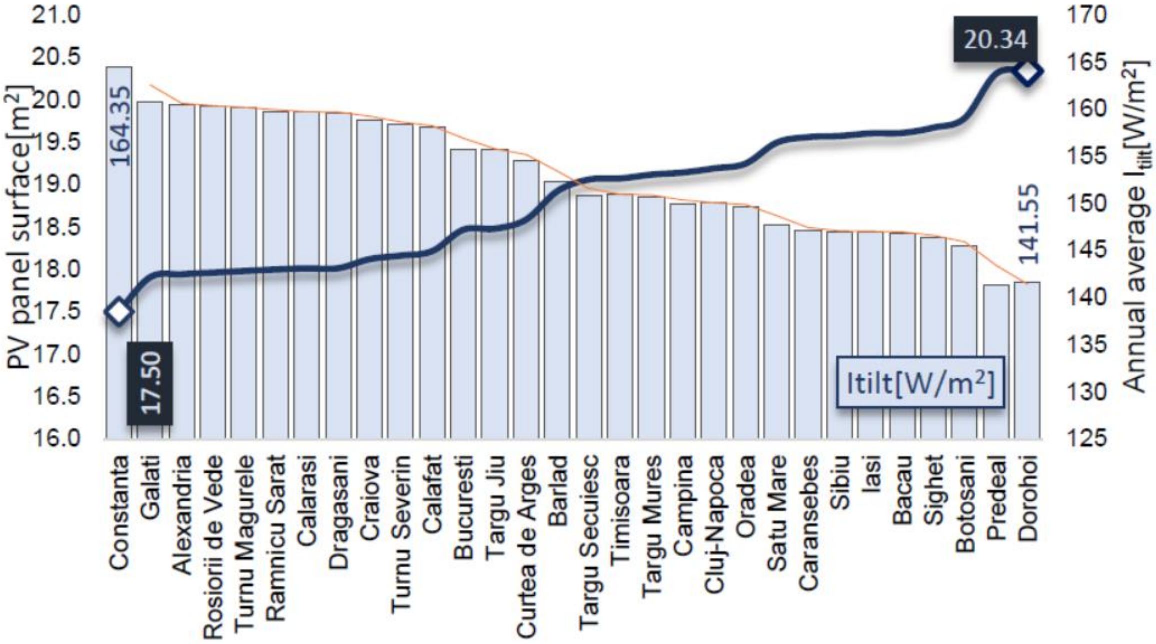

Figure 12

In figure 12 is plotted the annual average tilt solar radiation together with minimum surface to cover the total energy demand by each city. Can be observed on the graph that average tilted radiation over the year is a good indication of the PV panels amount required to satisfy the consumer energy needs.

When the net total solar surface of the PV panel, Atot, is reported towards daily demanded energy Ed,d, by equation 1.12 is obtained an important specific indicator defined by authors Consumer Specific Surface (CSS).

$$CSS = A_{tot}/E_{d,d} \qquad 1.11$$

Values of CSS are observed in figure 13, example of Constants stats is needed 1.61m^2 for each kWh of daily demanded energy. The parameter is obtained by a fixed value of demanded daily energy of consumer. The methodology proposes to be used an average daily consumption of the consumer during the year. In case consumer data is available for this period, using annual average of the daily consumption and with CSS from figure 13 the total net PV panels surface will be obtained. Therefor CSS is a quick method parameter to approximate each consumer needs by its location and by its daily demanded energy.

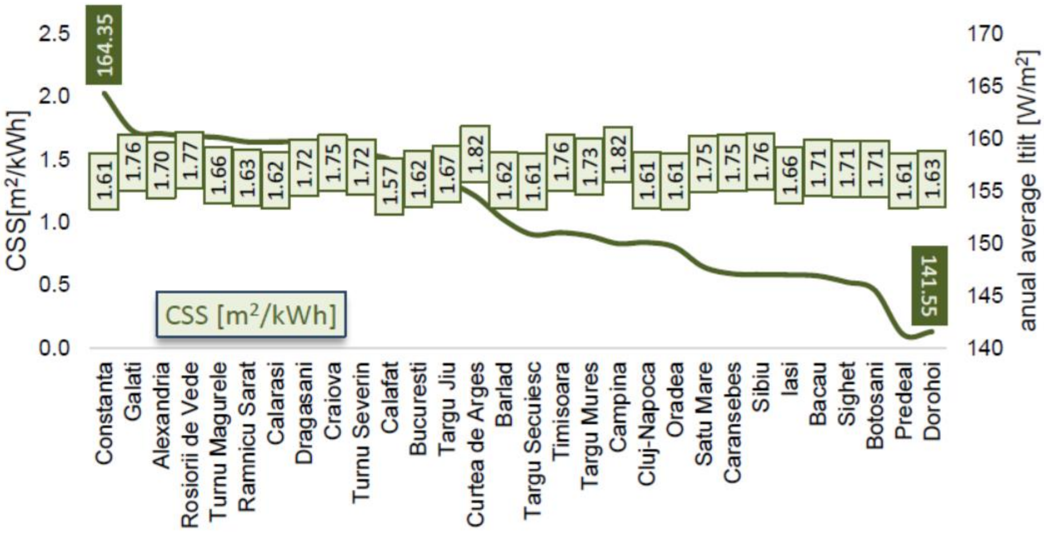

Figure 13

This study was extended to optimization of the system towards different tilt and azimuth angles. Thus, for azimuth angle between -90º and 90º with a 30º step, and for tilt angle from 30º to 60º with 5º step.

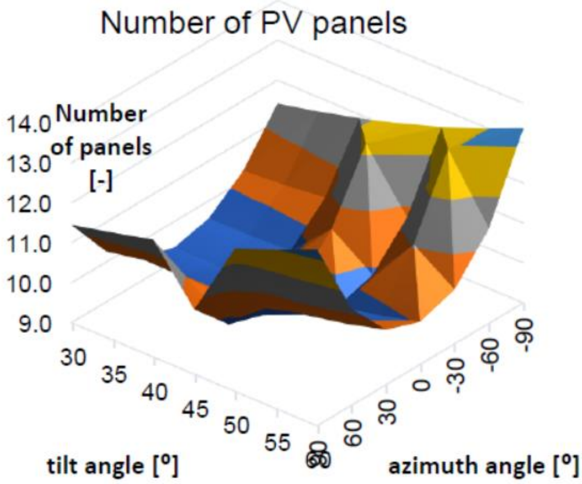

Figure 14

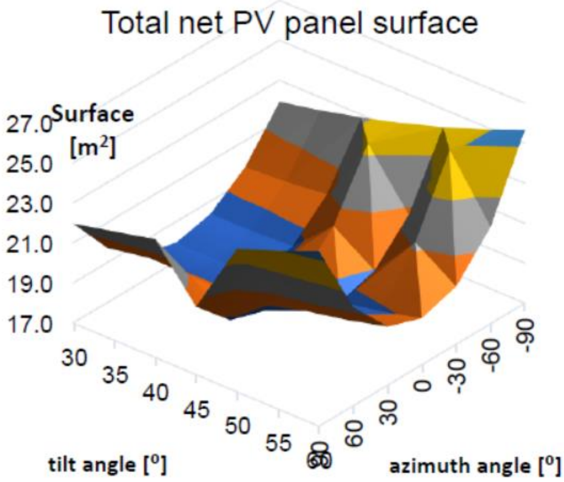

Figure 15

All the parameters proposed in this paper was evaluated for Bucharest location using the same horizontal solar radiation but with recalculation of each tilt solar radiation with above proposed values.

Both figures 14 respectively 15, number of PV panels and their net surface indicate the best mechanical installation with 30º tilted angle and 0º azimuth angle. Based on position of the building, impact on investment cost can be drastically high in case the azimuth angle cannot be reduced to South orientation, corresponding to 0º on the charts.

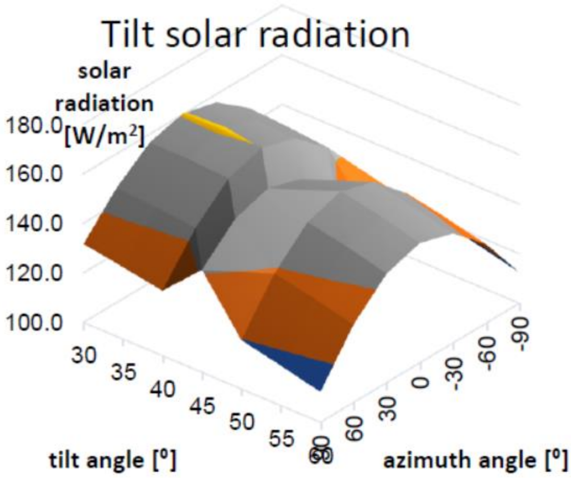

Figure 16

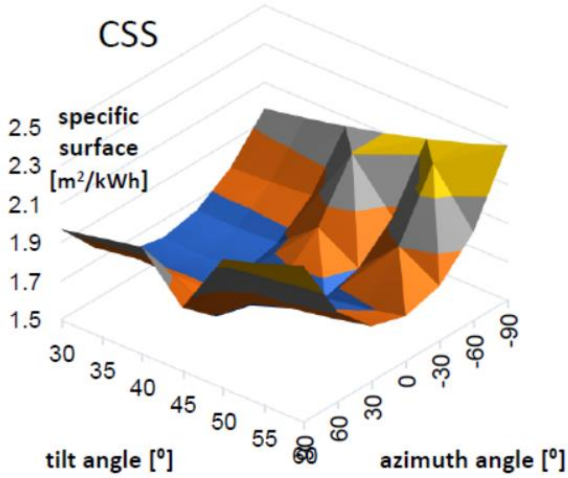

Figure 17

Tilt solar radiation represented in figure 16 denotes the values of annual average of tilted solar radiation when azimuth and tilt angles are changed. The chart help designers to extract an average tilt solar radiation based on mechanical characteristics of solar panels installation. With same distribution, the best installation respect same values above mentioned for azimuth and tilt angles. Figure 17 shows the distribution of CSS with angles change. With this chart, can be seen for Bucharest what is the consumer specific surface and easily calculation of required total net surface of PV panels based on equation 1.11, questioning the value of A_{tot}.

7. Discussions

Presented paper represent a simplified methodology for evaluation of PV system with regards to generated energy, overall energy demand coverage of the system analyzed, supplementary energy required from the grid and performances of the system when mechanical parameters are changed. Proposed equations and link with national methodology MC001 and its annexes, simplify the way a new system or an installed one can be analyzed. Thus, with charts values of thermal efficiency from Annex A2 and correction coefficient from Annex A1, using the horizontal solar radiation can be calculated the energy generation of the system for a specific location from Romania. Apparently, if horizontal or tilted solar radiation is available for other cities or location outside Romania, this simplified methodology can be successfully applied.

The paper proposes a quick evaluation for economical aspects too. Therefore, based on generated energy and energy prices, a refund period is possible to be calculated based on equation 1.11. Can be noted nowadays that with rise of energy prices, investments in such systems are rapidly reimbursed in periods of 4 to 5 years for common household appliances consumer.

Nomenclature

Latin symbols:
U_i – solar PV panel tilt angle, [º];
U_a – solar PV panel azimuth angle, [º];
A_{tot} – total net solar PV panels surface, [m^2];
$I_{T,\ Oriz.}$ – Horizontal solar irradiation established by Romanian Methodology MC001-volume I, annex A.9.6, [W/m^2];
I_{tilt} – Corrected tilt radiation based on horizontal radiation and correction factor. [W/m^2];
$P_{max,1000}$ – maximum PV Panel power, expressed for a solar irradiance 1000W/m^2, [W];
A_{pan} – net solar PV panel surface, [m^2];
I_{1000} –Standard Test Condition irradiance for PV panel efficiency evaluation [1000W/m^2]
ε_{PV} – PV panel efficiency, [-];
N_{zl} – month days number, [day];
N_p – number of PV panels used in evaluation, [-];
c_c– solar radiation correction coefficient, MC001 - annex A1, [-];
$C_{m,i}$ – monthly demanded energy, [kWh];
η_t – thermal efficiency of PV panel, MC001 - annex A2, [-];
η_{inv} – inverter efficiency, [-];
$p_{ref,year}$ – annual economy. [RON];
p_{kWh} – energy price, [RON];
p_{tax} – taxes for one kWh of consumed energy, [RON]
$E_{l,i}$ – monthly PV panel solar energy generation, [kWh];
$E_{PV\text{-}SEN}$ – PV energy injected in SEN over the year, [kWh];
$E_{PV\text{-}CON}$ – PV energy used by consumer over the year, [kWh];
$E_{tot,\ PV}$ – annual PV panel solar energy generation, [kWh];
$E_{d,d}$ – daily demanded energy, [kWh];
$E_{tot,\ d}$ – total demanded energy by consumer, [kWh];
$E_{tot,\ SEN}$ – total injected energy in the grid, [kWh];
E_{SEN} – supplementary energy required from the National Electrical Energy System, [kWh];

Greek symbols:

η_{inv}, inverter efficiency, [-];
$\eta_{t,\ PV}$ panel thermal efficiency, [-];
$\varepsilon_{PV,\ PV}$ panel efficiency, [-];

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