Maximal and Optimal DHW Production with Solar Collectors for Single Family Houses

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***Abstract* — The energy performance of newly erected buildings has radically improved in the last decade in Europe. The process will continue in the following years. It is partly induced by the 2010/31/EC directive [1] on the energy performance of buildings. The directive prescribes that all new communal buildings erected after 2019 and all communal and residential buildings after 2021 have to be built as nearly zero energy buildings (NZEB). The directive also requires that the energy demand of NZEB buildings have to be covered to a very significant extent by on-site or nearby renewable energy sources. Thus, the better knowledge on low and nearly zero energy buildings and integration of renewable energies are key issues nowadays. These buildings have some special characteristics compared to traditional buildings, therefore they require a special, more detailed modeling approach.**

I. Introduction

The utilization of solar energy in low energy buildings is fundamental due to the strict energy regulations, which favor the use of on-site or nearby produced renewable energy. Our paper focuses on solar energy utilization, which is a technically achievable option in most of the cases. There are two main ways to utilize solar energy. The first way is the passive use, which means that incoming energy is passively used for space heating. The second way is the active utilization, which means that an energy collecting device such as solar collector or PV panel is used. During the design process of a building it is important to accurately estimate the available solar energy, thus the energy demand for heating and cooling can be minimized and the energy produced on site could be maximized considering economical aspects. In this paper the solar energy potential of active solar thermal systems are examined in case of a single family house. Not only the solar yield, but also heat demands and system losses are analyzed.

II. Modeled Building, Meteorology and Calculation Method

A. Parameters of the modeled building

For this paper a typical, newly erected single family house was examined with three different orientations. The house fulfills the requirements of the Hungarian building code and also the energy requirements for NZEB buildings. The overall dimensions of the building are 18.75 x 8.5 m. The house is one storey high and has basement, where all HVAC appliances are placed. The basement is not heated, thus temperature varies throughout the year. The building has a pitched roof which has a 40° slope. The layout of the building and the maximal possible solar collector arrays for different orientations are shown in Figure 1.

The building has three bedrooms, two bathrooms, a utility room and a combined kitchen with living room along with a small entrance hall and an office room. The domestic hot water (DHW) system was planned for the building. The internal dimension of the DHW pipes is 20 mm and the total length is 57.6 m. For family houses the usual DHW storage tank size was considered, thus a widely used DINOXD USW-2 300 l tank was selected, covered with 10 cm heat insulation. The schematic illustration of the solar collector system is shown in Figure 2.

In the paper the maximal possible solar collector area was determined for the building, although this is economically not a viable solution. However in order to indicate the maximal possible energy production for single family houses this option should also be examined. For this case not only DHW demand and losses were taken into account as demand, but also the heating energy demand was considered. In case of NZEB buildings the usual values in Central-Europe for heating energy demand are 15 – 30 kWh/(m^{2}year). Although in Hungary the national regulation (based on the 2010/31/EC directive [1]) gives a definition for the NZEB building, in our paper a broader approach was applied. For the performed calculations heat demand of 15 and 30 kWh/(m^{2}year) were taken into account.

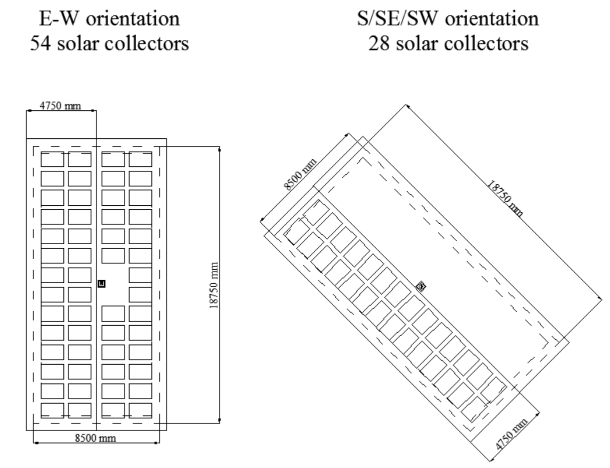

Figure 1. Layout of the building and the collector arrays for different orientations

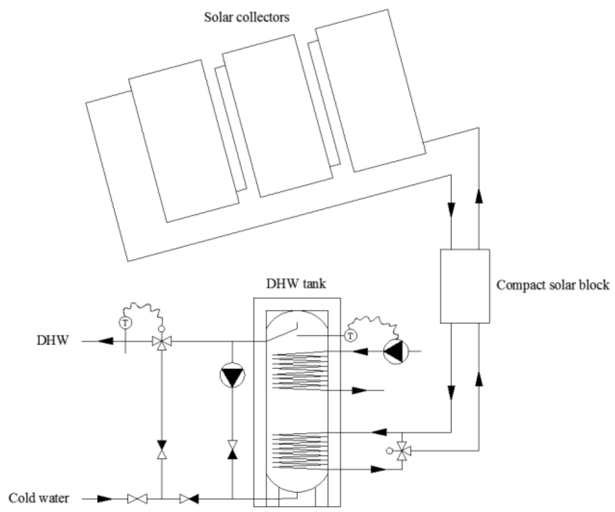

Figure 2. Schematic illustration of the solar collector system

B. Meteorological parameters building site, estimation of available solar radiation

The meteorological parameters for buildings basically depend on the building site. In this paper, the building was placed in the suburbs of Budapest. For the calculations two basic meteorological parameters, the monthly average of external temperature and the sum of global solar radiation are required. The average external temperature was calculated for the time period between 1981 and 2000, which data were taken from the Hungarian Meteorological Service database [2]. The incoming solar radiation was calculated based on sunny hours measurement data which was taken from the CarpatClim database, and the considered time period was from 1981 to 2010 [3]. There are several models to calculate solar radiation, from which 11 were compared in [4]. In the paper the models were examined for South orientation with 40° tilt angle. The models were compared at 4 different sky condition and the "relative performance of the individual models was determined by a combination of both statistical and graphical analysis." In the paper it was concluded, that the Hay model was performing "best under all sky, clear and partially cloudy conditions". According to the conclusions of model comparison in [4] the radiation calculations were performed with the Reindl et al. model [5], which is the improved version of the Hay model. In this model the global radiation is calculated as the sum of direct, diffuse and reflected radiation. In the model diffuse radiation consist of three parts:

- diffuse radiation from the sky dome
- circumsolar diffuse radiation
- diffuse radiation from the horizon.

The incoming radiation calculations were performed for every 15 minutes and the results were summed for each month of the year. The calculated monthly global radiation and average temperature for the building site is presented in Table 1. In the Reindl et al. model for monthly global solar radiation there is no difference between the calculated values for East and West and values for Southeast and Southwest oriented surfaces, due to the fact that the model is symmetric to the middle of the day. Thus, in case of east and west orientation the only difference in the global radiation is just in the time when it occurs during the day. For this reason, for the further calculations these orientation differences were not examined.

Table 1. Monthly values of monthly global radiation and average temperature

	Q_{sol} [kWh/(m^{2}month)]			$T_{i,e}$ [°C]
Orientation	E/W	SE/SW	S	-
Jan.	35.8	53.5	62.5	0.6
Feb.	52.7	73.6	83.6	2.2
Mar.	89.8	111.7	119.9	6.6
Apr.	126.0	142.3	144.5	11.9
May	160.6	167.3	163.5	17.0
June	167.1	167.1	160.7	19.8
July	175.4	178.9	172.8	22.1
Aug.	157.7	174.6	174.3	21.8
Sept.	111.7	137.7	145.7	17.1
Oct.	74.4	103.5	116.9	11.7
Nov.	39.7	58.6	68.0	5.4
Dec.	28.5	42.7	49.8	1.7

C. Calculation of energy demand and losses of the DHW system, and the estimated heating demand

DHW demand for the building was calculated based on the number of inhabitants: four inhabitants were considered which represent an average family. The energy demand calculations were based on the idea in [6]. The temperature of the DHW for the calculations was 50 °C, the cold water temperature was 11.6 °C, which is the yearly average temperature of the building site. The considered daily DHW consumption was 50 l/person, which is the standard value for Hungary. The DHW demand was calculated as in (1).

$$Q_{DHW} = c_w \cdot \rho_w \cdot \left(n_{pers} \cdot V_{DHW}\right) \cdot \left(T_{DHW} + T_{cw}\right) / 3600 \quad (1)$$

where:

Q_{DHW} – is the DHW demand [kWh/month]
c_w – is the specific heat of the water [kJ/(kgK)]
ρ_w – is the density of water [kg/m^3]
n_{pers} – is the number of inhabitants [-]
V_{DHW} – is the monthly DHW demand [m^3/person]
T_{DHW} – is the temperature of the DHW [°C]
T_{cw} – is the temperature of the cold water [°C]

For the DHW distribution the pipes were planned inside the floor in a protective tube without any insulation. The heat loss of pipes were calculated for different pipe depth and floor types and also for different temperature differences. As an average result 7 W/m was obtained as a specific heat loss for the distribution pipes. This result is applied for the whole building, regardless of the depth of the pipe and the floor type. In the building no circulation was planned, thus it was assumed that only in one fourth of the day has distribution heat losses. This assumption was made due to the fact that in the rest of the day there is no DHW use. The distribution losses were calculated according to (2).

$$Q_{DIST} = l_{pipes} \cdot q_{pipes} \cdot \tau_m \cdot / 4 / 1000 \quad (2)$$

where:

Q_{DIST} – is the distribution loss [kWh/month]

l_{pipes} – is the total length of the pipes [m]

q_{pipes} – is the specific loss of the pipes [W/m]

τ_m – is the number of hours in the month [h/month]

The specific heat loss of the storage tank was determined for the chosen DHW tank, the calculated value was 1.5 W/K. In order to determine the storage losses the monthly average temperature of the unheated basement had to be determined. The inner temperature of the basement was calculated for -13 °C and 36 °C external temperatures. Between the calculated values relationship is linear. The temperature of the basement was calculated for every month according to the average external temperature. The storage loss was calculated monthly according to (3) .

$$Q_{STOR} = q_{storage} \cdot (T_{DHW} - T_{basement}) \cdot \tau_m / 1000 \quad (3)$$

where:

Q_{STOR} – is the storage loss [kWh/month]

$q_{storage}$ – is the specific loss of the pipes [W/m]

T_{DHW} – is the temperature of the DHW [°C]

$T_{basement}$ – is the temperature of the basement [°C]

The total energy demand was calculated as the sum of the DHW demand and the distribution and the storage losses. The monthly heating demands were also calculated. The degree days for each month were calculated and the yearly demand was distributed accordingly. The calculated DHW demand and losses, along with the heating demand are presented in Table 2.

Table 2. Calculated energy demand of the DHW system and heating per building area [kWh/(m^{2}year)]

	Q_{DHW}	Q_{DIST}	Q_{STOR}	Q_{DEMAND}	Q_{H15}	Q_{H30}
Jan.	1.739	0.235	0.275	2.250	3.021	6.041
Feb.	1.571	0.213	0.245	2.028	2.506	5.011
Mar.	1.739	0.235	0.259	2.234	2.088	4.175
Apr.	1.683	0.228	0.236	2.147	0.607	1.214
May	1.739	0.235	0.230	2.205	0	0
June	1.683	0.228	0.215	2.127	0	0
July	1.739	0.235	0.217	2.191	0	0
Aug.	1.739	0.235	0.217	2.192	0	0
Sept.	1.683	0.228	0.223	2.134	0.443	0.886
Oct.	1.739	0.235	0.245	2.220	1.298	2.595
Nov.	1.683	0.228	0.254	2.165	2.199	4.398
Dec.	1.739	0.235	0.272	2.247	2.839	5.679
Year	20.5	2.8	2.9	26.1	15.0	30.0

D. Monthly energy yield of solar collectors, maximal and optimal case

To calculate the energy yield of solar collectors the previously described meteorological data and calculated DHW system parameters and monthly heat demand were used. For the calculation a widely used solar collector type, a Thermosolar TS 300 was considered. The energy yield of the solar collectors was calculated according to [7], however some additional data from [8] was also used. For the calculations the following collector and system parameters were used (Table 3):

Table 3. Solar collector and system parameters

Parameter	Value
η_0	0.8177
k_1	3.65
k_2	0.009
K_{dir} (50°)	0.95
FR	0.95
FR'/FR	0.8
T_{ref}	100 °C

With the previously described input parameters the energy yield of solar collectors were calculated. In (4) the temperature correction, in (5) the storage capacity correction was calculated.

$$\frac{X_{c1}}{X} = \frac{(11.6 + 1.18 \cdot T_{DHW} + 3.86 \cdot T_{cw} - 2.32 \cdot T_{i,e})}{(T_{ref} - T_{i,e})} \quad (4)$$

where:

X_{c1}/X – is the temperature correction factor [-]

$T_{i,e}$ – is the monthly average temperature [°C]

T_{ref} – is the reference temperature [°C]

$$\frac{X_{c2}}{X} = \left(\frac{V_{t,a}}{V_{t,opt}}\right)^{-0.25} = \left(\frac{0.7 \cdot V_t}{0.075 \cdot A_{coll}}\right)^{-0.25} \quad (5)$$

where:

X_{c2}/X – is the storage size correction factor [-]

$V_{t,a}$ – is the active storage capacity [m^3]

$V_{t,opt}$ – is the optimal storage capacity [m^3]

V_t – is the total storage capacity [m^3]

A_{coll} – is the total collector area [m^2]

The monthly solar fraction was calculated according to (6) with the use of (7), (8) and (9).

$$f_i = MIN\begin{pmatrix} 1.029 \cdot Y - 0.065 \cdot X_c - 0.245 \cdot Y^2 + \\ + 0.0018 \cdot X_c^2 + 0.0215 \cdot Y^3 ; 1 \end{pmatrix} \quad (6)$$

$$Y = \eta_0 \cdot Q_{sol} \cdot FR' / FR \cdot K_{dir}(50°) \cdot A_{coll} / Q_{DEMAND} \quad (7)$$

$$X_c = X \cdot (X_{c1} / X) \cdot (X_{c2} / X) \quad (8)$$

$$X = \begin{pmatrix} \left(FR \cdot k_1 + FR \cdot k_2 \cdot \left(T_{DHW} - T_{i,e}\right)\right) \cdot FR' / FR \cdot \\ \cdot \left(T_{ref} - T_{i,e}\right) \cdot \tau_m \cdot A_{coll} / Q_{DEMAND} / 1000 \end{pmatrix} \quad (9)$$

where:

f_i – is the monthly solar fraction [-]

η_0, k_1, k_2, $K_{dir}(50°)$ – are collector parameters [-]

FR, FR', T_{ref} – are solar system parameters [-]

Q_{DEMAND} – is the total energy demand of the DHW system [kWh/month]

The energy produced by solar collectors are calculated for every month as in (10)

$$Q_{coll} = f_i \cdot Q_{DEMAND} \quad (10)$$

The calculations were performed for three separate cases. In the first case the total roof area was covered with solar collectors as shown in Figure 1. In this case the produced thermal energy was calculated for three options. In the first option only the DHW demand was supplied by the solar collector system, in the second and third options both DHW and heating demand was supplied. The only difference between these options was the heating demand, as in one case it was 15 (H15) and in the other it was 30 (H30) kWh/(m^{2}year).

For the second case only the DHW system's demand was taken into consideration. In this option the number of collectors were reduced to the amount which is necessary to still achieve the value of 1 for the yearly solar fraction with maximal system efficiency. In this case only the DHW system's demand was considered as thermal energy demand.

The third case was an optimized case, for which the system was designed for an economically feasible solution: acceptable solar fraction at affordable cost. The following boundary conditions were made:

- the number of collectors has to be an integer
- the annual system efficiency (η_{system}) is maximal
- the monthly solar share has to be greater than 0.9 and less than 0.95 in June, July and August.

In this option only the DHW demand was supplied by the solar collector system, and the optimization was made for only this option.

III. Results of the Calculations

The results of performed calculations for separate cases are presented in Table 4. In the first case for South and Southeast/Southwest orientations there are 28 collectors placed on the building, in case of the East/West orientation 54 (A_{coll}=1.78 m^2 per piece). From the table it is clearly visible, that in the first case the total DHW demand of the house can be supplied, however with just a really low system efficiency. If solar collectors are used for space heating as well, it can be stated, that in case of South and Southeast/Southwest orientations the energy demand cannot be supplied only by solar collectors throughout the year. In case of the East/West oriented building enough solar collectors can be placed on the roof to supply the DHW and heating energy demand of the building. This is due to the fact that in case of East/West oriented building the maximal number of placed collectors is nearly the double of what can be placed in the other examined orientations.

In the second case, when the number of collectors were reduced, it can be seen that without reducing solar fraction the number of collectors can be reduced by at least 42.9%, and the system efficiency can be increased from 3.92-7.55% to 10.44-13.9%.

In the third case the rational optimization of solar collectors is done. By this optimization process, optimal number of collectors were determined for all three orientations. In every case the optimal number of collectors were 3. This means that the number of collectors were reduced from the first case by 89.3% and 94.4% and compared to the second case by 81.3% and 85.7%. System efficiency is the highest in this case due to the fact that this case has the lowest collector area, thus the smallest amount of incoming solar energy but the DHW system's demand is the same in all cases. The number of collectors for each case are presented in Figure 3.

For the optimal case the monthly results for different calculations are presented in Figure 4, Figure 5 and Figure 6. From these diagrams it is clearly visible that in summer, regardless of the orientation, 90% of the DHW system's demand is covered. The orientation differences are significant in winter, when the East/West oriented collectors barely operate, while in case of the other orientations still at least 10% of the DHW demand can be supplied.

Table 4. Calculated results for the different cases (A_{coll}=1.78 m^2)

Case	Collector array, supplied system(s)	Orientation	Nr. of coll.	f_i	η_{sys}
I.	Maximal, DHW	S	28	1	7.55
		SE/SW	28	1	7.55
		E/W	54	1	3.92
	Maximal, DHW+H15	S	28	0.992	12.69
		SE/SW	28	0.976	12.20
		E/W	54	1	6.72
	Maximal, DHW+H30	S	28	0.846	11.89
		SE/SW	28	0.814	10.63
		E/W	54	1	9.53
II.	Maximal optimized, DHW	S	16	1	13.90
		SE/SW	16	1	13.22
		E/W	21	1	10.44
III.	Optimal, DHW	S	3	0.624	35.17
		SE/SW	3	0.596	32.41
		E/W	3	0.503	24.98

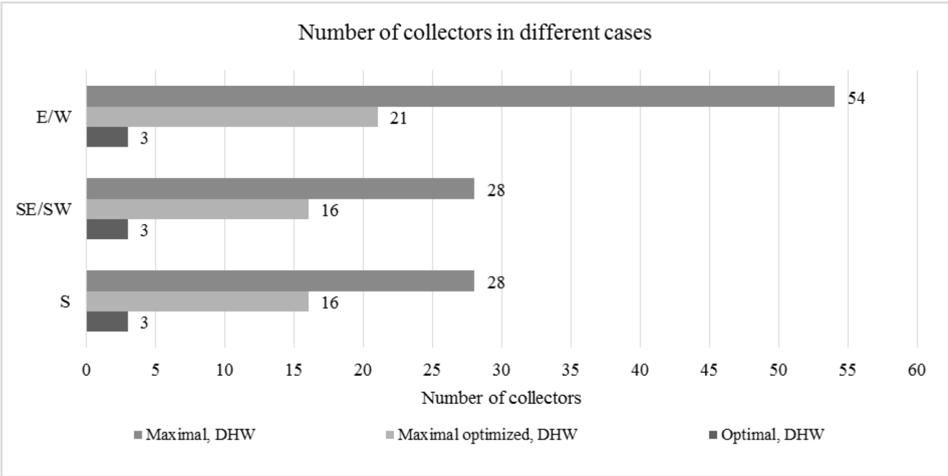

Figure 3. The number of collectors in different cases

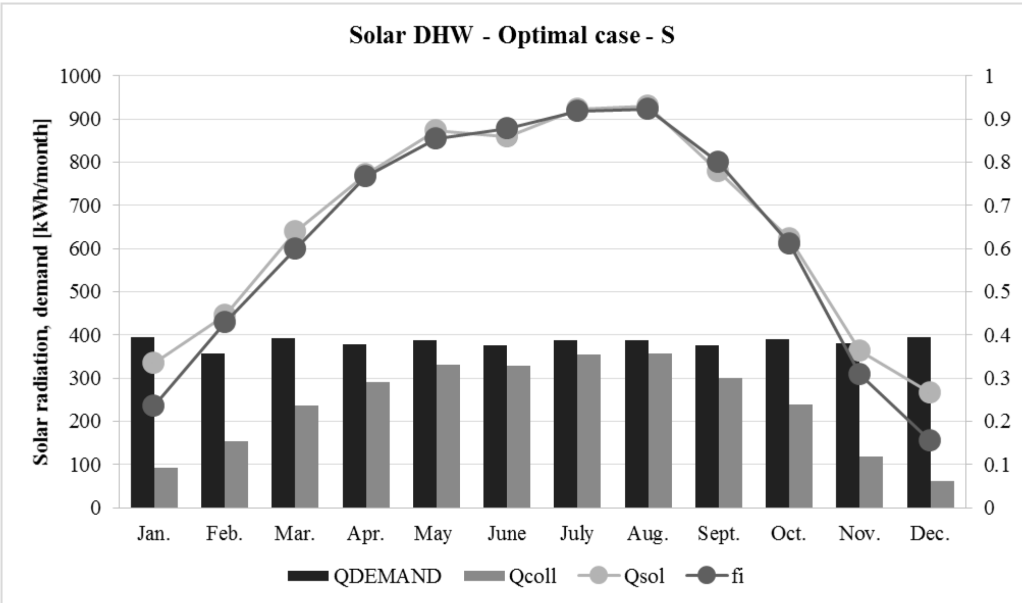

Figure 4. Monthly results for South oriented building with optimized number of collectors

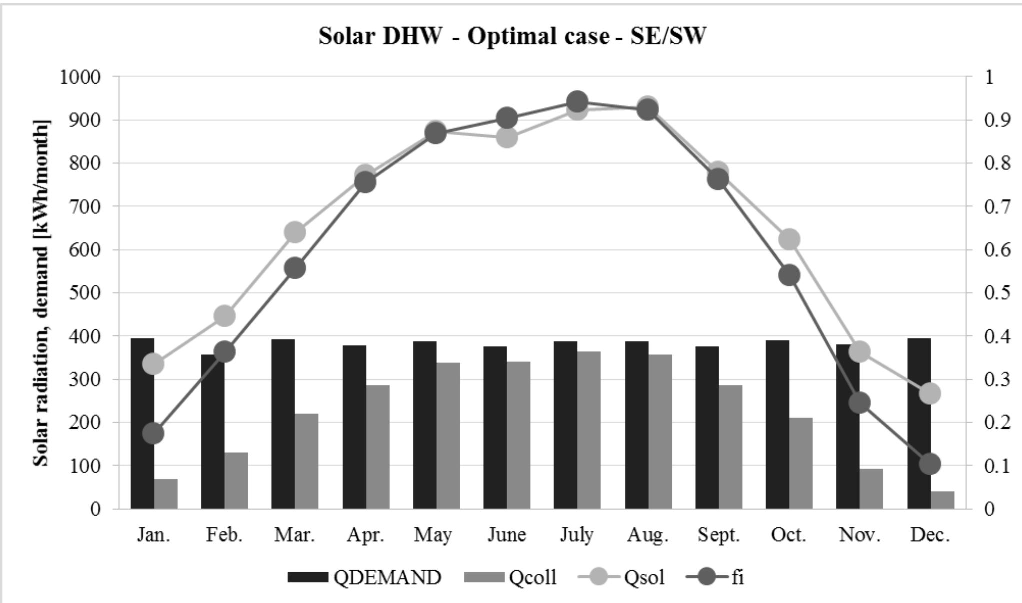

Figure 5. Monthly results for Southeast/Southwest oriented building with optimized number of collectors

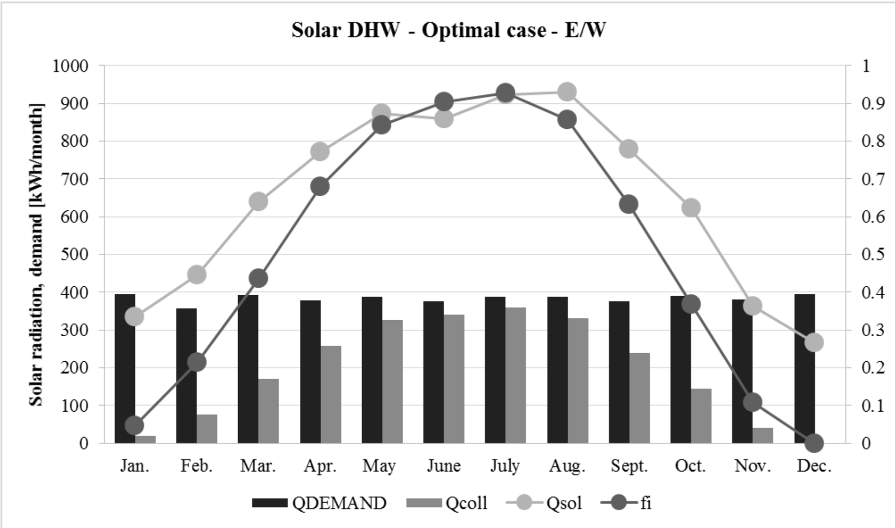

Figure 6. Monthly results for East/West oriented building with optimized number of collectors

IV. Conclusion

In the paper three different solar collector arrays were examined for a single family house. In the first case the total roof area was covered with collectors and the produced thermal energy was calculated for three different demands. In the second case the number of solar collectors were determined which are able to fulfill the DHW demand throughout the year. In the third case the optimization of the collector number was performed with the following boundary conditions: the system efficiency has to be highest for the year and the solar fraction in the summer months have to be higher than 90%.

In the second case when the number of collectors were reduced it can be concluded that in any orientation from East to West the number of collectors can be reduced by at least 42.9%. The system efficiency is increasing in this case from 3.92-7.55% to 10.44-13.9% and the investment costs decrease due to the lower number of panels.

In the third case the rational optimization of the solar collectors are done. By this optimization process the optimal number of collectors were determined for all three orientations. In every case the optimal number of collectors were 3. This means that the number of collectors were reduced, compared to the first case by 89.3% and 94.4% and compared to the second case by 81.3% and 85.7%. In this case the total solar coverage is not achieved, but the investment costs are drastically lower compared to the other cases.

References

[1] Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast)

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