Optimal Domestic Solar Space and Water Heating System in Çeşme

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Received: 06.04.2017 Accepted:07.05.2017

Abstract- Solar hot water and space heating systems have been an important energy conservation technique in buildings, along with improving insulation efficiency of building envelopes and HVAC systems. According to statistical data from EU, installations of solar hot water heating systems have been increased gradually. The purpose of this study is to illustrate quantitatively the feasibility of optimal space and water heating system using solar energy. The house is assumed to be located in Çeşme, Turkey, where 1304 kWh/m^2-year of solar radiation for the period of 2734 h/year is measured. Considering the space heating and hot water demand in this geographic location, solar collector and storage capacity are optimized using *f*-Chart method. The results showed that a 92% of the total energy demand can be covered by solar energy.

***Keywords*:** *Solar space, heating system, optimization, f*-Chart method, *Turkey*

Nomenclature

τ	:	Transmittance Coefficient
A	:	Area (m2)
A_c	:	Collector area (m^2)
C	:	Specific heat of water (J/ kg ^{0}C)
D_w	:	Water demand per person per day (1/day person)
F	:	Annual solar fraction
F'_R	:	Collector–heat exchanger efficiency factor
fi	:	Monthly solar fraction
F_R	:	Collector heat removal factor
H_T	:	Monthly average daily radiation on the collector per unit area (J/m^2)
l	:	Liters
L	:	Annual total heating load (J)
L_i	:	Monthly total heating load (J)
N	:	Number of people
Q_s	:	Heat demand for space heating (W)
Q_w	:	Heat demand for hot water production (kCal/day)
T_a	:	Monthly average ambient temperature (^{0}C)
T_d	:	Desired temperature of heated water (^{0}C)
T_n	:	Temperature of network water (^{0}C)
T_{ref}	:	An empirically derived reference temperature (100^{0}C)
U	:	Overall heat transfer coefficient (W/m^2 K)
U_L	:	Overall heat transfer coefficient (W/m^2 K)
V	:	Storage capacity (l/m^2)
α_i	:	Convection coefficient of inner surface (W/m^2 K)
α_o	:	Convection coefficient of outer surface (W/m^2 K)
Δt	:	Total number of seconds in the month
ΔT	:	Temperature difference
λ_n	:	Thermal conductivity (W/mK)

1. Introduction

Being one of the main pillars of renewable energy sources, solar energy offers clean and sustainable energy for the present and certainly for the future energy demands. There is a resurgence of interest in solar energy due mainly to the alarming level of global warming and increasing fossil fuel costs.

Located in the sunny belt of Mediterranean region between 36^{0}N and 42^{0}N latitudes with an abundant and reliable supply of solar energy, Turkey possesses an excellent solar energy potential based on the long-term data measured by the State Meteorological Services and mapped by General Directorate of Electrical Power Resources Survey and Development Administration (EIEI) as shown in Fig. 1 [1].

Table 1 shows the distribution of solar radiation in seven geographical regions of Turkey. The average annual solar radiation is measured as 1311 kWh/m²-year (3.6 kWh/m²-day or 308.0 cal/cm^2-day). To expose and estimate solar energy potential in Turkey compiling long term metrological measurements with scientific and engineering methodologies have recently been the subject of many research studies [2,3,4].

In retrospect, the solar energy utilization has not been proportional to the solar potential in the country. Table 2 shows the solar energy contribution within the total energy consumption. The flat plate collectors for the domestic hot water are the major solar energy utilization system. Solar energy contribution column given in Table 2 is therefore energy substitute.

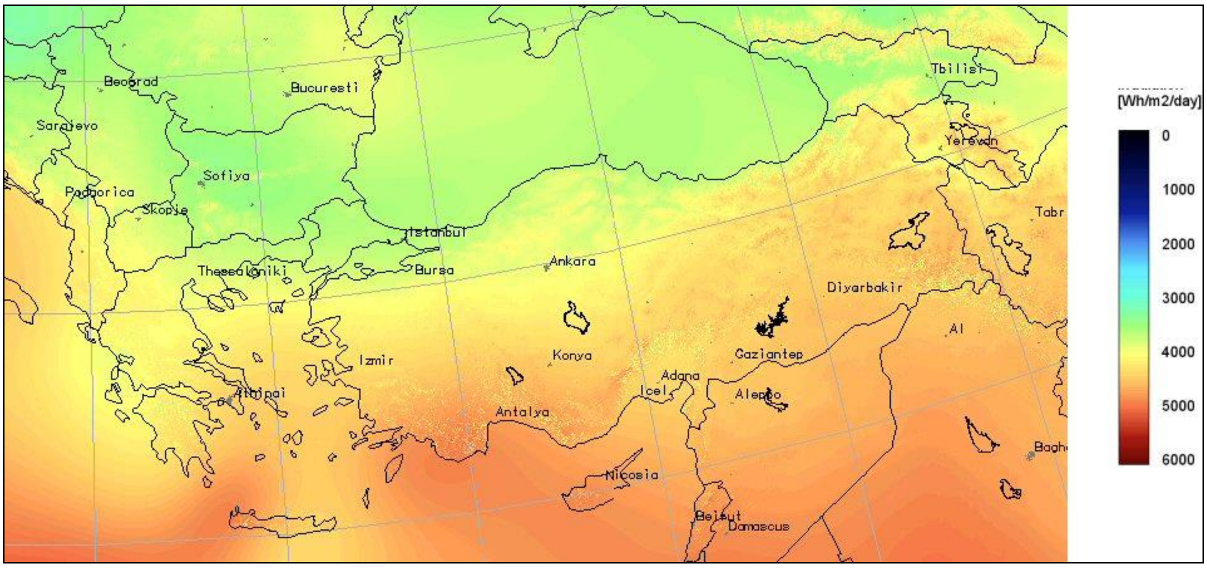

Fig. 1. Solar Radiation for the Eastern Mediterranean and Turkey

Table 1. Regional Distribution of Solar Energy Potential of Turkey

Region	Total Solar Radiation (kWh/m^2-year)	Sunshine Duration (hours/year)
Southeastern Anatolia	1460	2993
Mediterranean	1390	2956
East Anatolia (East)	1365	2664
Central Anatolia	1314	2628
Aegean (West)	1304	2738
Marmara (North-W)	1168	2409
Black Sea (North)	1120	1971

Source: General Directorate of EIEI, www.enerji.gov.tr

Turkey is one of the leading countries in the world with a total installed collector area. The solar energy utilization and its share in the total energy consumption are expected to grow in the future due mainly to EU funds and state incentives in the renewable energy utilization. All future energy projections show how important it is to make technological and research manpower investment to renewable energy sources since the fossil fuels will melt down within the foreseeable future.

Table 2. Solar energy consumption in Turkey

Year	Solar Energy Contribution (thousand TOE)	Total Energy Consumption (thousand TOE)	Solar Percentage in Total (%)
1998	210	74709	0.281
1999	236	74275	0.317
2000	262	80500	0.325
2001	287	75402	0.380
2004	375	83826	0.447
2006	403	99825	0.403

Source: Ministry of Energy and Natural resources, www.enerji.gov.tr

The purpose of this study is to illustrate quantitatively the feasibility of optimal space and water heating system using solar energy in a house located in a sunny belt region. A house is designed and assumed to be located in Çeşme, a town in the Aegean region of Turkey. The construction and insulation materials are chosen from present building material market. The relationship between solar collector and storage which are the most important parts of the solar system, are investigated in a reasonable formulation by using f-Chart method. It is shown that most of the energy demand has been met by solar system if the optimal collector area and storage capacity values are used.

To date many studies are conducted on energy-efficient buildings. The aim in the design of these buildings is to decreasing energy expenses, see for example [5,6]. Space heating and hot water production consumes more than one third of the primary energy in industrialized countries like Germany. Therefore, conservation of fossil fuels and emission reduction may be enhanced significantly by solar thermal technology [7].

2. Brief Description of the Architecture and Materials Used

The building designed is assumed to be 200 m2 (20 m x 10 m). The height of the house is 2.8 meters. Architectural design is made carefully to maximize solar gains and to decrease heating loads. It is critically significant that house is well insulated to control losses in the building. Therefore, many construction materials are used in the residential building’s design. To protect and save the energy, materials have been chosen carefully.

There are 20 identical windows, each of which is 0.96 meters squared (1.2 m x 0.8 m) and uses double glazed glasses with air gaps in between to prevent energy loses. Outer walls are made of aerated concrete line cement plaster and insulation material. The total area for walls is 144.4 square meters. The floor of building consists of alum, concrete, insulation material, cement plaster, and lime sandstone. Floor is 200 meters squared. Roof is made of concrete, insulation material and lime cement plaster. Roof is 200 square meters. There are two doors in the building which are made of metal and well insulated. Each door is 2.2 square meters. When the roof area is not sufficient collectors may be placed on land.

The materials used in construction are carefully selected so that the thermal conductivity with respect to the thickness of the materials are calculated. Then, heating load is computed according to TS825 (Turkish Standards) for determination of the heating load in buildings for each month separately. The hot water demand for each month is calculated. And sum of these two terms for each month will give the amount of energy is to be supplied for each month as monthly total heating load for space heating and hot water.

3. Space Heating Calculations

Heat is a sort of energy and as explained in the second law of thermodynamics. Heat transfers from the hotter medium to colder medium, without requiring any external forces. In construction materials, heat transfer usually consists of conduction and convection. Firstly, heat transfer from room to wall surface by convection, then by conduction at the inside of wall, and lastly from the outer surface of wall to outside of the building by convection.

The heat loss of the building is to be found for determining of the space heating. First, the overall heat transfer coefficient U-value of the parts of building being in contact with the ambient is to be calculated using Eq. 1 below.

$$\frac{1}{U}=\frac{1}{\alpha_i}+\frac{d_1}{\lambda_1}+\frac{d_2}{\lambda_2}+\ldots+\frac{d_n}{\lambda_n}+\frac{1}{\alpha_o} \qquad (1)$$

The temperature of room is usually higher than the ambient temperature. Heat transfers from building to outside. Therefore, in these calculations, the necessary heat demand is calculated to keep the rooms’ temperature at a desired value. The desired value of the rooms’ temperature is assumed to be 20 °C. For calculating the heat demand for space, we used Eq.2 [8]:

$$Q_s = A \cdot U \cdot \Delta T \tag{2}$$

The heat demand together with building specific area and overall heat transfer coefficient U-values are given for each month in Tables 3 and 4.

The average ambient temperatures of June, July, August, and September are recorded as 24.4, 27.4, 27.0, and 22.8 °C, respectively. During these months, the space heating is not required.

3.1. Hot Water Production

Water heating is a thermodynamic process using an energy source. To calculate the energy for hot water production at the temperature of network city water of Izmir, and the desired temperature value after heating has to be decided. Usually, 45 °C is anticipated for the hot water. But, in this project the hot tap water is designed as 55 °C to avoid bacterial growth [9].

The monthly temperature of the city water network of Izmir is given in Table 5 (based on Turkish Standards TS 3817). The hot water demand for different types of buildings is shown in Table 6.

It is assumed that there are four people in the house; two parents and two children. A 60 liter/day per person is assumed for hot water demand. The heat flow calculation is based on Eq.3 below.

$$Q_w = N \cdot D_w \cdot C \cdot (T_d - T_n) \tag{3}$$

Monthly water heating requirements are then calculated and presented in Table 7.

3.2. Total Heating Load

After these results, the total heating load for space and hot water can be calculated by adding the energy demand of space heating and the energy demand for the hot water production. The results are shown in Table 8.

4. Application of F-Chart Method for the Solution of the Problem

In order to predict the monthly and annual solar fraction of active solar heating systems, an appropriate calculation procedure is needed. The f-chart method is one of the most comprehensive and widely used tool and it is suitable for such predictions. The f-chart method provides a mean for estimating the fraction of a total heating load that will be supplied by solar energy for a given solar heating process [9]. The method is a correlation of the results of the many hundreds of thermal performance simulations of solar heating systems.

It is worth noting that f-chart is widely used as a standard method such that new methods are compared to the f-Chart method, see [9-12]. For example Hawas and Abou-Zeid (1983) developed a general chart (R-Chart) for sizing collectors of solar heating systems and compared their results with those from f-Chart. They concluded that the results of their R-Chart method have a good agreement with the f-Chart method in all cases. Similarly, Ajona and Gordon [11] developed an analytic model for the long-term performance of solar air heating systems and showed the comparison with the f-Chart method. The comparison of results for the annual solar fraction (f) calculated with their analytic model and those corresponding f-Chart results was also presented graphically.

The conditions of the simulations are varied over appropriate ranges of parameters of practical system designs. The resulting correlations give f, the fraction of the monthly heating load (for space heating and hot water) supplied by solar energy as a function of two dimensionless parameters. One, X, is related to the ratio of collector losses to heating loads, and the other, Y, is related to the ratio of absorbed solar radiation to heating loads.

The f-Chart method for active solar heating systems is based upon certain system configurations and some assumed values for the system parameters. The monthly solar fraction, f, is correlated to two easily calculated dimensionless variables X and Y. The variables X and Y are given in Eq.4 and 5 [9].

$$X = F_R \cdot U_L \cdot \frac{F'_R}{F_R} \cdot \left(T_{ref} - \overline{T}_a\right) \cdot \Delta t \cdot \frac{A_c}{L} \tag{4}$$

$$Y = F_R \cdot (\tau \cdot \alpha)_n \cdot \frac{F'_R}{F_R} \cdot \frac{\overline{(\tau \cdot \alpha)}}{(\tau \cdot \alpha)_n} \cdot \mathrm{H_T} \cdot \frac{A_c}{L} \tag{5}$$

The monthly solar fraction f can be determined from Eq.6 which has been obtained from the regression analysis [13].

$$f = 1.029.Y - 0.065.X - 0.245.Y^2 + 0.0018.X^2 + 0.0215.Y^3 \tag{6}$$

Table 3. Space heating calculations for January-May

		January			February			March			April			May		
	Area (m^2)	**ΔT (K)**	**U (W/m^2K)**	**Q_s (W)**	**ΔT (K)**	**U (W/m^2K)**	**Q_s (W)**	**ΔT (K)**	**U (W/m^2K)**	**Q_s (W)**	**ΔT (K)**	**U (W/m^2K)**	**Q_s (W)**	**ΔT (K)**	**U (W/m^2K)**	**Q_s (W)**
Floor	200	13.5	0.307	828.9	10.9	0.307	669.3	8.6	0.307	528.0	4.5	0.307	276.3	0.5	0.307	30.7
Roof	200	13.5	0.302	815.4	10.9	0.302	658.4	8.6	0.302	519.4	4.5	0.302	271.8	0.5	0.302	30.2
Window	19.2	13.5	2.6	673.9	10.9	2.6	544.1	8.6	2.6	429.3	4.5	2.6	224.6	0.5	2.6	25.0
Door	4.4	13.5	4.0	237.6	10.9	4.0	191.8	8.6	4.0	151.4	4.5	4.0	79.2	0.5	4.0	8.8
Wall	144.4	13.5	0.425	828.5	10.9	0.425	668.9	8.6	0.425	527.8	4.5	0.425	276.2	0.5	0.425	30.7
			Total	**3384.3**			**2732.5**			**2155.9**			**1128.1**			**125.4**

Table 4. Space heating calculations for October-December

		October			November			December		
	Area (m^2)	**ΔT (K)**	**U (W/m^2K)**	**Q_s (W)**	**ΔT (K)**	**U (W/m^2K)**	**Q_s (W)**	**ΔT (K)**	**U (W/m^2K)**	**Q_s (W)**
Floor	200	3.1	0.307	190.2	7.5	0.307	460.5	8.8	0.307	540.3
Roof	200	3.1	0.302	187.2	7.5	0.302	453.0	8.8	0.302	531.5
Window	19.2	3.1	2.6	154.8	7.5	2.6	374.4	8.8	2.6	439.3
Door	4.4	3.1	4.0	54.6	7.5	4.0	132.0	8.8	4.0	154.9
Wall	144.4	3.1	0.425	190.2	7.5	0.425	460.3	8.8	0.425	540.1
			Total	**777.1**			**1880.2**			**2206.1**

Table 5. City of Izmir water network temperature

Month	Jan.	Feb.	Mar	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
T_n (^{0}C)	12.3	11.5	13.1	16.6	21.2	26.2	29.8	31.0	29.0	24.9	20.4	15.1

Table 6. Hot water demand for different types of buildings

Type of Building	**Description**	**Demand (l/day-person)**
Domestic	Low income	40-60
	Middle income	60-100
	High income	100-150
Hotel	Average	100
	Luxurious	200
Factory	Average	50
	Washbasin	30
	Shower	50

Table 7. Q_w values for months

	January	**February**	**March**	**April**
Q_w Equ.	4*60*1*(55–12.3)	4*60*1*(55–11.5)	4*60*1*(55–13.1)	4*60*1*(55–16.6)
kcal/day	10,248	10,440	10,056	9,216
J/day	42,877, 632	43,680,960	42,074,304	38,559,744
	May	**June**	**July**	**August**
Q_w Equ.	4*60*1*(55–21.2)	4*60*1*(55–26.2)	4*60*1*(55–29.8)	4*60*1*(55–31)
kcal/day	8,112	6,912	6,048	5,760
J/day	33,940,608	28,919,808	25,304,832	24,099,840
	September	**October**	**November**	**December**
Q_w Equ.	4*60*1*(55–29)	4*60*1*(55–24.9)	4*60*1*(55–20.4)	4*60*1*(55–15.1)
kcal/day	6,240	7,224	8,304	9,576
J/day	26,108,160	30,225,216	34,743,936	40,065, 948

Table 8. Total heating load for each month

Month	Jan.	Feb.	Mar	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
L_i (GJ)	10.4	7.8	7.1	4.1	1.4	0.9	0.8	0.8	0.8	3.0	5.9	7.2

Empirical correlation given in Eq.6 has been proposed for a standard storage capacity of 75 liters stored water per square meter of collector area. The performance of systems with storage capacities in the range of 37.5 to 300 l/m2 can be determined by multiplying the dimensionless group X by a storage size correction factor Xc/X as given Eq.7 [8].

$$\frac{X_c}{X} = \left(\frac{V}{75}\right)^{-0.25} \tag{7}$$

The fraction of the annual heating load supplied by solar energy F is the sum of the product of monthly solar energy fraction fi and the monthly thermal load Li divided by the annual load L:

$$F = \left(\frac{\sum f_i \cdot L_i}{\sum L_i}\right)^{-0.25} \tag{8}$$

Table 9. Meteorological data for Çeşme

Month	$\overline{T}_a$ (^{0}C)	H_T (MJ/m^2-day)
January	6.5	8.4
February	9.1	9.2
March	11.4	13.8
April	15.5	20.5
May	19.5	25.7
June	24.4	27.0
July	27.4	26.8
August	27.0	23.7
September	22.8	18.2
October	16.9	13.5
November	12.5	8.0
December	11.2	6.2

All the elements of the dimensionless parameters are known, except collector area and storage capacity. And Table 10 presents the computation of dimensionless parameters for each month based on Meteorological data for Çeşme given in Table 9.

Table10. X_c and Y values

January	February	March
$X_c = 0.095 * A_c * (V/75)^{-0.25}$	$X_c = 0.111 * A_c * (V/75)^{-0.25}$	$X_c = 0.131 * A_c * (V/75)^{-0.25}$
$Y = 0.019 * A_c$	$Y = 0.025 * A_c$	$Y = 0.046 * A_c$
April	May	June
$X_c = 0.210 * A_c * (V/75)^{-0.25}$	$X_c = 0.605 * A_c * (V/75)^{-0.25}$	$X_c = 0.855 * A_c * (V/75)^{-0.25}$
$Y = 0.115 * A_c$	$Y = 0.435 * A_c$	$Y = 0.687 * A_c$
July	**August**	**September**
$X_c = 0.955 * A_c * (V/75)^{-0.25}$	$X_c = 0.960 * A_c * (V/75)^{-0.25}$	$X_c = 0.983 * A_c * (V/75)^{-0.25}$
$Y = 0.793 * A_c$	$Y = 0.701 * A_c$	$Y = 0.521 * A_c$

October	November	December
$X_c = 0.291 * A_c * (V/75)^{-0.25}$	$X_c = 0.151 * A_c * (V/75)^{-0.25}$	$X_c = 0.130 * A_c * (V/75)^{-0.25}$
$Y = 0.107 * A_c$	$Y = 0.031 * A_c$	$Y = 0.020 * A_c$

5. Optimization and Results

To perform the optimization properly, collector area and storage capacity have to be the variables of the empirical correlation [14-16]. To be able to do this, corrected X values, Xc, are used instead of X values in the empirical correlation. The correlation then becomes

$$f = 1.029.Y - 0.065.X - 0.245.Y^2 + 0.0018.X_c^2 + 0.0215.Y^3 \quad (9)$$

The correlation, f, is a non-linear equation with two unknowns; collector area and storage capacity.
The fraction of the annual heating load supplied by solar energy is the objective function of this study. f is, simply, the ratio of the annual heat demand supplied by solar system to total heating load, i.e. the solar savings. Consequently, the objective function, f, has to be a maximized, because of the fact that increasing f value means producing more energy by the solar system.
Three constraints are determined as;

$$10 \le A_c \le 150$$

$$37.5 \le V \le 300$$

$$5 < F_R A_c \le 120$$

The first one upper and lower value of the collector area and the second is the storage capacity. The third is the actual constraint for optimization.
Optimization of this correlation is performed by using MATLAB optimization toolbox. Optimization has been performed in three steps. As a result, the optimum values of collector area and storage capacity are found as:
$A_c = 131.89\ m^2$
$V = 41.35\ l/m^2$
And annual heating load supplied by solar energy, f, is calculated as 0.92. This result means, the annual solar fraction will be 0.92 if collector area is 131.89 m^2 and the storage of tank is 5453.65 liters. In other words, if these optimum values of collector area and storage capacity are used in this house, 92% of the annual energy demand of the house for space and water heating would be covered by the solar energy.

6. Conclusion

There are many studies [14-17] regarding to the solar heating applications. This study is carried out for domestic solar heating in Çeşme.
Residential and office space and water heating system consumes approximately 33% of the total energy according to the official reports of Ministry of Energy in Turkey (www.enerji.gov.tr). This study has shown that when properly designed, contribution of the solar radiation could be a significant energy source for the domestic space and water heating. The house considered in this study was quite typical house in Çeşme, as 200 m^2 gross areas with the height of 2.8 m. The building materials were also typical regional materials but were assumed to be observing national standards. A collector area of 131.89 m^2 and the storage tank of 5453.65 liters were found to be optimum sizes to meet the space and hot water demand under these favorable conditions. As a result, a 92% of the total heat demand is to be covered by the solar energy. Even if this result may be evaluated under Cesme's climatologic conditions, utilization of solar energy will reduce the energy bill significantly and contribution of using solar energy to the world ecosystem should be appreciated in any climatologic location.

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