# Solar Thermal Water Heating for Domestic or Industrial Application (New Trend Modeling)

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**Abstract**

This paper presents a modeling of Solar Water Heating ( SWH ) used for domestic or industrial application using Flat– Plate Collectors.
The research uses a new trend of application for Solar Radiation variation during the day, The model is a ( Half– Sine ) Model for clear day with some assumptions to predict the temperature fluctuation in the Storage tank and to calculate the heating energy demand to be added to the Solar energy supplied by Sun.
An encouraging result has been found that will help the designer to have a good idea and give useful indication about the system proposal to make a proper economic analysis of any projects.

## منظومة التسخين الحرارية الشمسية للتطبيقات المنزلية والصناعية ( نموذج بإتجاه جديد )

**الخلاصة**

هذا البحث يقدم نموذج لمنظومة تسخين ماء تعمل بالطاقة الشمسية تستخدم للأغراض المنزلية أو الصناعية بإستخدام الواح التجميع المستوية (Flat – Plat Collector).
تم في هذا البحث إستخدام تطبيق جديد لتغير الطاقة الشمسية خلال النهار, الموديل المستخدم هو الجيب النصفي (Half – Sine) لنهار شمسي مشرق مع بعض الفرضيات من أجل تخمين تقلبات أو تغيرات درجة حرارة حوض التخزين (Storage Tank) وذلك لحساب الطاقة الحرارية المطلوب إضافتها إلى الطاقة الشمسية المجهزة من الشمس.
لقد كانت النتائج مشجعة والتي يمكن أن تساعد المصمم للحصول على فكرة جيدة و مؤشرات ملائمة حول المنظومة المقترحة وإستنتاج التحليل الإقتصادي الملائم لأية منظومة أو مشروع.

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## 1. Introduction

The need for new source of energy becomes more important in our present time because of:

- The increasing prices of fossil energy and their future shortage.
- Using of fossil energy causes the Global – Warming due to the pollution with $CO_2$.

The substitution of fossil energy sources by renewable energies nowadays is the world main concern to pass this problem.

The sun is considered as a source of renewable clean energy, as well it represents a free source of energy and to be one alternative for fossil energy. The solar water heating system is the technique used to collect the heat coming from the sun, it is highly effective and pollution free technology.

Solar technologies are commonly grouped into three major categories, differing in the ways they collect, store and use energy. These technologies are Passive Solar [the direct utilization of the sun's radiation as light (skylights) or heat (greenhouses)], Solar Thermal (store thermal energy for later use (include domestic & industrial water heating, space heating) and the last category is the photovoltaic cells which convert the sunlight to electricity.

The focus of this paper is the solar thermal water heating for domestic and industrial heating by predicting the output storage tank temperature of a *Solar Thermal Hot Water Heating System*.

## 2. The Research Goal

The goal of this research is to carry out a study and examine the solar thermal water heating systems and to reach for an economical analysis to design an appropriate solar water heating system for domestic, building and industrial applications, as well as a simplified modeling approach developing and final results are discussed to see which parameter has more impact on the those systems.

## 3. The Solar Thermal water Heating System:

The solar water heating system is designed to collect the sun's energy and transferring it to the water circulating either for immediate use or as a storage medium to be kept in a storage tank for later use or demands. The main components of the solar water heating system are:

- The solar collector panels, they are considered here in this paper ***Glazed Flat Plates***.
- The insulated storage tank and heat exchanger.

These components are shown in figure (1) below; it describes also the operation and the function of this type of system, and however a storage tank with an external heat exchanger could also be used separately.

Basic system operation involves a pump for circulating the heat transfer fluid such as water or may be a food safe water / glycol mixture through the solar collector to heat it up. The hot fluid then passes through the heat exchanger built in the storage tank to warm up the cold feeding water (***city water***) before it is re-circulated back to the collector through the pump. The feeding water is constantly being heated while the system is in operation until it is required. The water is drawn from the storage tank for any purpose such as domestic or industrial process, and it will be then replenished with cold feeding water which in turn warms up by the heat exchanger.

The solar thermal system works as a pre-heater for the feeding water supply to reduce the thermal load on the main hot water heater such as boiler or auxiliary heater but it is doesn't replace or compensate them. So it could be considered as a saving energy device and to ensure a warm or hot water at a desired temperature.

## 4. The Theoretical Analysis for the Storage Tank Temperature:

To analyze the storage tank temperature, it should first of all work to calculate the solar energy that can be collected. This energy is introduced to heat up the storage tank temperature which in turns is compared with the reference temperature for required processes to see if any additional heat should be added by the auxiliary heater or not. To study this case figure (**2** ) above is applied to represent a simplified schematic for solar model ***(System Configuration)***. Then to reach to a general formula for the Storage Tank Temperature and how it is changed with time ( ***24 hour period*** ) the ***solar intensity*** which plays the major impact in this analysis should be known, the ***load information*** is required to size the system.

### 4.1. The Heat Balance for the Storage Tank:

The water inside the storage tank is assumed to be well mixed and not stratified during heating up process in any way (the assumption will affect the result's accuracy, and the deviation can be obtained with actual application). The model loop is shown in figure ( **2** ) above and the firm equation will be derived below using simple energy balance along with mass flow and heat capacity for each stream and component s. The heat balance equation for the storage tank is:

$$- M_{st} \cdot C_{pw} \cdot \frac{dT_{st}}{dt} =$$
$$- m_{co} \cdot C_{pg} \cdot [T_{co} - (T_{st} + \Delta T)] +$$
$$m_s \cdot C_{pw} \cdot (T_{st} - T_{feed}) + q_L$$

Where:

- **$M_{st}$** = Mass of the water in storage tank (kg)
- **$C_{pw}$** = Specific heat for the Water (W. sec / kg. $^oC$) = 4184
- **$T_{st}$** = Storage tank water temp. ($^oC$)
- **t** = Time (sec)
- **$m_{co}$** = Mass flow rate through the collector (kg/s)
- **$C_{pg}$** = Specific heat for the Water or water / glycol mixture in collector (W. sec / kg. $^oC$)
- **$T_{co}$** = Collector outlet temp. of the Water or water / glycol mixture ($^oC$)
- **$\Delta T$** = The driving force temperature difference [according to **ref. (1)** its approximately range between (3 – 5 $^oC$)]
- **$m_s$** = Mass flow rate through the storage tank (kg/s)
- **$T_{feed}$** = City Water or feed water temp. to the storage tank ($^oC$)
- **$q_L$** = The heat losses from the storage tank & heat exchanger losses (W)

our model ignores the effect of the tank size and assume all energy extracted by the solar panels is useful, and simply multiplied by the heat exchanger efficiency (**ε** ). This that means we let the heat loss (**$q_L$**) as a fraction of the useful energy of the heat exchanger ( **$Q = m_{co} . C_{pg} . [ T_{co}$**

**– ($T_{st}$ + ΔT)]** ), then the above equation becomes:

$$- M_{st} \cdot C_{pw} \cdot \frac{dT_{st}}{dt} = - m_{co} \cdot C_{pg} \cdot [T_{co} - (T_{st} + DT)].e + m_s \cdot C_{pw} \cdot (T_{st} - T_{feed})$$

$$\frac{dT_{st}}{dt} = K_1 \cdot [T_{co} - (T_{st} + DT)] - K_2 \cdot (T_{st} - T_{feed})$$

$$\frac{dT_{st}}{dt} + (K_1 + K_2) \cdot T_{st} = K_1 \cdot T_{co} + K_2 \cdot T_{feed} - K_1 \cdot DT$$

By using the parameter notation (**D** ) and rearranging the above equation, it yields to:

$$DT_{st} + K_3 \, . \, T_{st} = K_1 \, . \, T_{co} + K_2 \, . \, T_{feed} - K_1 \, . \, \Delta T \quad \ldots\ldots (1)$$

**Where:**

- $e$ = The Heat exchanger & storage tank efficiency.
- $K_1$ = constant ( 1 / sec ) = constant * 3600 ( 1 / hour ).
- $K_2$ = constant ( 1 / sec ) = constant * 3600 ( 1 / hour ).
- $K_3$ = $K_1 + K_2$ ( 1 / sec ) = constant * 3600 ( 1 / hour ).

$$K_1 = \frac{m_{co} \cdot C_{pg} \cdot e}{M_{st} \cdot C_{pw}}$$

$$K_2 = \frac{m_s}{M_{st}} , \qquad K_3 = K_1 + K_2$$

### 4.2. The Heat Balance for Pump

The pump raises the flow rate temperature before it reaches the solar collector (fig. 2 above), the heat balance equation is:

$$m_{co} \, . \, C_{pg} \, . \, [\, T_{ci} - (\, T_{st} + \Delta T \,)\,] = P$$

$$T_{ci} = K_4 \, . \, P + T_{st} + \Delta T \quad ..(2)$$

Where:

- $P$ = The pump power (W)
- $T_{ci}$ = Collector inlet water temp. (°C)
- $K_4$ = constant ( °C / W )

$$K_4 = \frac{1}{m_{co} \, . \, C_{pg}}$$

### 4.3. The Heat Balance for the Solar collector ( *Glazed Flat Plate* ):

Referring to figure (2) above, the useful energy ( $Q_s$ ) in watts gains from the sun as an incident solar radiation ( $I_t$ ) on the collector will be absorbed by the collector flow rate ( $m_{co}$ ), the heat balance equation is as follows:

$$Q_s = m_{co} \, . C_{pg} \, . (T_{co} - T_{ci})$$

But ( $Q_s$ ) is also found within acceptable accuracy limits for the ***Glazed Flat Plates*** (***ref. 1, 2, 3,4 & 5***) in terms of weather conditions ( $I_t$ ) and inlet temperature ( $T_{ci}$ ) to be equal to:

$$Q_s = A_c \, . \, [\, F_R \, (\, \tau \, \alpha \,) \, . \, I_t - F_R \, U_L \, . \, (\, T_{ci} - T_a \,)\,]$$

Where:

- $A_c$ = Collector aperture area ($m^2$)
- $F_R (t \ a)$ = Solar Absorptivity coefficient is a number between **0** and **1** (Dimensionless)
- $F_R \ U_L$ = Thermal Loss coefficient (W/m$^2$ .°C)
- $I_t$ = The Global solar radiation (W/m$^2$)
- $T_a$ = The ambient temp. (°C)

From the above two equations, we obtain the following equation:

$$m_{co} \, . \, C_{pg} \, . \, (\, T_{co} - T_{ci} \,) = A_c \, . \, [\, F_R \, (\, t \ a \,) \, . \, I_t - F_R \, U_L \, . \, (\, T_{ci} - T_a \,)\,]$$

Rearranging the above equation and solving for the collector outlet temperature ( $T_{co}$ ) we will obtain:

$T_{co} = K_5 . T_{ci} + K_6 .I_t + K_7 . T_a$ .. ( 3 )

**Where:**

- § $K_5$ = Constant (Dimensionless)
- § $K_6$ = Constant (m$^2$ . $^o$C / W)
- § $K_7$ = Constant (Dimensionless)

$$K_5 = 1 - \frac{A_c \cdot F_R U_L}{m_{co} \cdot C_{pg}}$$

$$K_6 = \frac{A_c \cdot F_R (t a)}{m_{co} \cdot C_{pg}}$$

$$K_7 = \frac{A_c \cdot F_R U_L}{m_{co} \cdot C_{pg}}$$

Substituting eq. ( **3** ) into eq. ( **1** ), it yields to:

$$DT_{st} + K_3 . T_{st} = K_1 . [ K_5 . T_{ci} + K_6 . I_t . + K_7 . T_a ] + K_2 . T_{feed} - K_1 . \Delta T$$

$$DT_{st} + K_3 . T_{st} = K_1 . K_5 . T_{ci} + K_1 .K_6 . I_t . + K_1 . K_7 . T_a + K_2 . T_{feed} - K_1 . \Delta T \quad ... (4)$$

Substituting eq. ( **2** ) for the collector inlet water temperature ( $T_{ci}$ ) into eq. ( **4** ) that yields to:

$$DT_{st} + K_3 . T_{st} = K_1 . K_5 . [ K_4 . P + T_{st} + \Delta T ] + K_1 .K_6 . I_t . + K_1 . K_7 . T_a + K_2 . T_{feed} - K_1 . \Delta T$$

$$DT_{st} + K_{12} . T_{st} = K_8 . I_t + K_9 . P + K_{10} . T_a + K_2 . T_{feed} + K_{11} . \Delta T$$

Simplifying the above equation and rearranging it, we will obtain a new differential equation which governs the relation between the storage tank temp.( $T_{st}$ ), and the global solar radiation ( $I_t$ ), as shown in the below equation in the equation below:

$DT_{st} + K_{12} . T_{st} = K_8 . I_t + K_{13}$ ... ( 5 )

**Where:**

- § $K_8$ = $K_1 . K_6$ = Constant (m$^2$ . $^o$C / W. sec) = Constant * 3600 (m$^2$ . $^o$C / W. hour)
- § $K_9$ = $K_1 . K_4 . K_5$ = Constant ($^o$C / W .sec) = Constant * 3600 ($^o$C / W. hour)
- § $K_{10}$ = $K_1 .K_7$ = Constant (1 / sec) = Constant * 3600 (1 / hour)
- § $K_{11}$ = $K_1 . ( K_5 - 1 )$ = Constant (1 / sec) = Constant * 3600 (1 / hour)
- § $K_{12}$ = $K_3 - K_1 . K_5$ = Constant (1 / sec) = Constant * 3600 (1 / hour)
- § $K_{13}$ = Constant (1 / sec) = Constant * 3600 (1 / hour)

$$K_8 = \frac{A_c \cdot F_R (ta).e}{M_{st} \cdot C_{pw}}$$

$$K_9 = \frac{e}{M_{st} \cdot C_{pw}} . \left( 1 - \frac{A_c \cdot F_R U_L}{m_{co} \cdot C_{pg}} \right)$$

$$K_{10} = \frac{A_c \cdot F_R U_L \cdot e}{M_{st} \cdot C_{pw}}$$

$$K_{11} = - \frac{A_c \cdot F_R U_L \cdot e}{M_{st} \cdot C_{pw}}$$

$$K_{10} = - K_{11}$$

$$K_{12} = \frac{m_s \cdot C_{pw} + A_c \cdot F_R U_L \cdot e}{M_{st} \cdot C_{pw}}$$

$$K_{13} = K_9 . P + K_{10} . T_a + K_{11} . \Delta T + K_2 . T_{feed}$$

The constant ( $K_{13}$ ) is depends mainly on the pump power ( $P$ ), the ambient temp.( $T_a$ ) in which it will be taken as the average daily day temperature during the sun shine (from the sunrise time to sunset time), the driving force temp. difference ( $\Delta T$ ) and the City water or Feeding water temperature ( $T_{feed}$ ) in which it will be estimated latter on, all of these parameters are considered constants.

Equation ( **5** ) is a Non – Homogenous Linear differential equation of first order with constant coefficients. The non – homogeneity is due to the presence of the dependant variable ( $I_t$ ) the global solar radiation which is a function of time ( $t$ ), to solve equation ( **5** ), we should know this relation.

The simple Half – Sine Model of clear – day solar irradiance (***ref. 2***) is all that needed to predict the solar energy system design. The only input required is the times of sunrise, sunset and the peak noontime solar irradiance. The model state is as follows:

$$I_t = I_{noon} \cdot \sin\left(\frac{\pi \cdot (t - t_{sunrise})}{(t_{sunset} - t_{sunrise})}\right)$$

**Where:**

- $I_{noon}$ = The peak noontime Solar Irradiance (W / m$^2$)
- $t_{sunrise}$ = The Sunrise time (Hour)
- *tsunset = The Sunset time (Hour)*
- $t$ = *Time (Hour)*

Letting the sunrise time ( $t_{sunrise}$ ) to be the zero time, then ( $\Delta t = t_{sunset} - t_{sunrise}$ ) represents the daylight time and the above equation for ( $I_t$ ) becomes:

$$I_t = I_{noon} \cdot \sin\left(\frac{\pi \cdot t}{\Delta t}\right) \quad \ldots\ldots (6)$$

Substituting eq. ( **6** ) into eq. ( **5** ), we will obtain:

$$(D + K_{12}) \cdot T_{st} = K_8 \cdot I_{noon} \cdot \sin\left(\frac{\pi \cdot t}{\Delta t}\right) + K_{13} \quad \ldots\ldots (7)$$

Equation ( **7** ) has two solutions, the Complementary function and the Particular Integral (***ref. 6***), it is easy to see that the Particular Integral solution is:

$$Y_P = E + A \cdot \sin\left(\frac{\pi \cdot t}{\Delta t}\right) + B \cdot \cos\left(\frac{\pi \cdot t}{\Delta t}\right)$$

$$Y'_P = K_{14} \cdot \left\{A \cdot \cos\left(\frac{\pi \cdot t}{\Delta t}\right) - B \cdot \sin\left(\frac{\pi \cdot t}{\Delta t}\right)\right\}$$

**Where:**

$$K_{14} = \left(\frac{\pi}{\Delta t}\right)$$

Substituting for ( $Y_p$ & $Y_p'$ ) into eq. (**7**) and solving ( $E$, $A$ & $B$ ), it is found that:

$$E = \frac{K_{13}}{K_{12}}$$

$$A = \left(\frac{K_8 \cdot K_{12} \cdot I_{noon}}{(K_{12}^2 + K_{14}^2)}\right)$$

$$B = -\left(\frac{K_8 \cdot K_{14} \cdot I_{noon}}{(K_{12}^2 + K_{14}^2)}\right)$$

Then, to find a complete solution for the homogeneous equation of equation ( **7** ) by letting it equal to zero:

$$(D + K_{12}) \cdot T_{st} = 0$$

It is natural to find out that the complete solution of homogenous equation mentioned above is:

$$T_{st-c} = C \cdot e^{-K_{12} \cdot t}$$

Then the general solution for equation ( 7 ) is:

$$T_{st} = C \cdot e^{-K_{12} \cdot t} + \frac{K_{13}}{K_{12}} + \frac{K_8 \cdot I_{noon}}{\left(K_{12}^2 + K_{14}^2\right)} \cdot \left\{ K_{12} \cdot \sin\left(\frac{p \cdot t}{Dt}\right) - K_{14} \cdot \cos\left(\frac{p \cdot t}{Dt}\right) \right\} \quad \ldots\ldots (8)$$

The arbitrary constant **(** $C$ **)** can be obtained by applying the initial condition at the beginning of the heating process by the Solar Energy which is:

$$At \quad t = 0 \quad \rightarrow \quad T_{st} = T_i$$

Where **(** $T_i$ **)** is the initial storage tank temperature. Substituting equation (8) the general equation and solving for **(** $C$ **) yields**:

$$C = T_i - \frac{K_{13}}{K_{12}} + \frac{K_8 \cdot K_{14} \cdot I_{noon}}{\left(K_{12}^2 + K_{14}^2\right)}$$

Rearranging the general solution to have the final form for **(** $T_{st}$ **)** which becomes:

$$T_{st} = T_i \cdot e^{-K_{12} \cdot t} + C_1 \cdot \left(1 - e^{-K_{12} \cdot t}\right) + I_{noon} \cdot \left\{ C_2 \cdot \left(e^{-K_{12} \cdot t} - \cos\left(\frac{p \cdot t}{Dt}\right)\right) + C_3 \cdot \sin\left(\frac{p \cdot t}{Dt}\right) \right\} \quad \ldots\ldots\ldots (9)$$

**Where:**

$$C_1 = \frac{K_{13}}{K_{12}} ,$$

$$C_2 = \left(\frac{K_8 \cdot K_{14}}{\left(K_{12}^2 + K_{14}^2\right)}\right)$$

$$C_3 = \left(\frac{K_8 \cdot K_{12}}{\left(K_{12}^2 + K_{14}^2\right)}\right)$$

### 4.4. The Heat Balance of the Storage Tank after sunset time (off time):

When the sun is set out, the solar irradiance will become zero, the pump is stopped and the flow rate **(**$m_{co}$ = 0**)**, then the hot water in the storage tank can be used and compensate the feeding water**(** $T_{feed}$ **)**. To study the heat balance of such a case, figure ( **3** ) is applied schematically as shown below.

In this model we will work to represent the heat loss **(** $q_L$ **)** as a fraction **(** $f$ **)** of the useful heat **[** $Q_{useful} = m_s \cdot C_{pw} \cdot (T_{st\text{-}off} - T_{feed})$ **]** given by the storage tank. The storage tank water temperature will decline to approach with time to the feeding water temperature **(**$T_{feed}$**)**.

$$-M_{st} \cdot C_{pw} \cdot \frac{dT_{st}}{dt} = Q_{useful} + q_L$$

Letting **(** $q_L = f \cdot Q_{useful}$ **)**, then we get:

$$-M_{st} \cdot C_{pw} \cdot \frac{dT_{st}}{dt} = (1 + f) \cdot m_s \cdot C_{pw} \cdot \left(T_{st-off} - T_{feed}\right)$$

Rearranging and using the parameter notation ( $D$ ), the above equation will become as follows:

$$(D + K_{15}) \cdot T_{st-off} = K_{15} \cdot T_{feed} \quad \ldots\ldots\ldots (10)$$

**Where:**

- $f$ = The heat loss fraction.

- $T_{st\text{-}off}$ = The storage tank water temperature at the off–time ( °C ).
- $K_{15}$ = Constant (1 / sec) = Constant * 3600 (1 / hour)

$$K_{15} = \frac{(1+f)\,.m_s}{M_{st}}$$

The solution of the above equation (**10**), can be simply obtained and approved with the boundary condition which states that at ( time $t$ **= 0** , the initial temperature **(** $T_{i\text{-}off}$ **)** is equal to **(** $T_{st}$ **)** at the end of the sunset ), the time **(** $t$ **)** range will begin at sunset to sunrise time, that yields :

$$T_{st\text{-}off} = T_{i\text{-}0ff} \cdot e^{-K_{15}\cdot t} + \left(1 - e^{-K_{15}\cdot t}\right) \cdot T_{feed} \qquad \text{......... ( 11 )}$$

**5. Design Considerations** in this paragraph a sample of calculation will be put into practice for Baghdad City. First of all, we should know the designed thermal load, from this point the other factors will be found or proposed. So if we take a small domestic or industrial process water demand based on daily consumption of **(** $m_s$ **= 10000** *liter/day* **= 10000/ (24* 3600) = 0.116** *l/sec* **or 0.116** *kg/sec***)** with reference temperature **(** $T_{ref}$ **= 60** *°C* **)**, then the load is (***ref. 2, 4 & 5***):

$$Q_{load} = m_s \;.\; C_{pw} \;.\; (\, T_{ref} - T_{feed} \,) \qquad \text{........ ( 12 )}$$

The feeding water temperature**(** $T_{feed}$**)** which is supplied by the public water systems can be used to calculate the energy needed. It can be calculated from the minimum and maximum average monthly ambient temperatures based on weather Database ( Meteorological Database ). It is assumed that the ***soil temperature*** at an appropriate depth ( ***2 meters depth*** ) is equal to the feeding water temperature **(** $T_{feed}$ **)** (***ref. 4***), it is expressed as:

$$T_{feed} = \frac{(T_{min} + T_{max})}{2} - \frac{(T_{max} - T_{min})}{2} \cdot \left\{ h \;.\; \cos\left( 2\pi \;.\; \frac{n-2}{12} \right) \right\} \qquad \text{... ( 13 )}$$

**Where:**

- $T_{min}$ = The minimum average monthly ambient temperature (°C)
- $T_{max}$ = The maximum average monthly ambient temperature (°C)
- $h$ = 1 for Northern Hemisphere and ( -1 ) in the Southern Hemisphere
- $n$ = the month number (i. e, Jan = 1 …… Dec. = 12)

Table **( 1 )** below represents the Average monthly ambient temperature calculated from Meteorology Database for Baghdad City ( **year 2000** ) and **(** $T_{feed}$ **)** from the above equation (**13**), where fig. ( **4** ) shows them graphically.

Figure ( **4** ) shows that the feeding water temp. It is equal to average monthly ambient temp. with a time lag of one month due to the soil resistance and temperature fluctuation of the day and month.

Using eq. ( **12** ), then **(** $Q_{load}$ **)** can be calculated for each month, figure (**5** ) below shows the load energy required for each month. It appears that the maximum load required reached in February was (**24.59 kW**) and the minimum was August (**10.8 kW** ).

In order factors sach as the system cost and collector size should be balanced. If the system is designed for colder winter months, the number of collectors (***collector's area***) represents the system cost prohibitive and the overheating in summer and vice versa for summer design. The ideal heating system design is to supply about **70 – 80%** of the total yearly water heating load (***ref. 7***). For simplicity, we will consider here the summer design of (**10.8 kW**) on which our calculations ware based.

To find the total collectors area **(** $A_c$ **)** required to produce the designed thermal load **(** $Q_{load}$ **)**, it will be proposed as a thumb of rules getting from experiences or estimated according to the following equation which will be used (***ref. 7***):

$$A_c = \left(\frac{Q_{load}}{\eta \, . \, I}\right) . \left(\%\,Solar\,Availability\right) \qquad \text{.......... (14)}$$

Where:

- $\eta$ **=** The collector efficiency
- $I$ **=** The Average monthly Insolation ( $W/m^2$ )
- ***% Solar Availability*** = the percent of daily insolation available due to obstructed solar window.

To find the Average monthly Solar Insolation ***( I )***, we will consider **August** as a reference month ( solar flux in summer months is more constant than in winter months ), and from the Meteorology Database for Baghdad City **(year 2000)**, we found that ***(I = 235 W/m²)***, figure (**6**) below shows the monthly variation in Solar Insolation of August.

For the efficiency ( $\eta$ ), it can be found on manufacturer's specification sheets or from the Solar Rating and Certification Corporation **(SRCC)**, we will use an efficiency value of **( 0.45 )** which is an average of all the efficiencies of the brands (ref. 6 ). The *%Solar Availability* is assumed to be equal to **( 100% )** for unobstructed solar window. Thus the total collector area **(** $A_c$ **)** can be obtained to be equal to:

$$A_c = 10800 \, / \, ( 0.45 * 235 )$$

$$= 102 \ m^2$$

To find the Collector's numbers to be used in this calculation, we should choose the standard area of the collector, this parameter is the manufacturer's specification and should be taken from collector's brochures, it is mostly equal to (2.87 $m^2$) which is the aperture area for standard flat – plat with a dimension ( 8 ft x 4 ft ) (ref. 1), and thus the collector's no. is:

$$\text{Collector's no.} = 102 \, / \, 2.87 \approx 36$$

These collectors (***Glazed Flat – Plates***) will be flushed mounted horizontally on the Building roof in parallel array, so enough space should be taken into consideration for this arrangement.

The Storage Tank capacity (size) depends on the system used, it can roughly be estimated to be equal to **(0.05 to 0.075 m³ / m² of the collector area)** (***ref. 5***), thus it will be equal to **( 3 m³ or 3000 Liter )**. Most Glazed Flat plate collectors are provided with values of **(** $F_R(\tau\alpha)$ **) = 0.68 to 0.75 &** $F_U R_L$ **= 4.9 to 5.247 W/m². °C )** (***ref. 1 & 4***) , choosing **(** $F_R(\tau\alpha)$ **= 0.75 &** $F_U R_L$ **= 5.247 W/m² . °C )** to be used in our calculation.

For the other parameters to be used in equations ( **9 & 11** ), we will estimate or propose them. The average daylight ambient temperature **(**$T_a$**)** for **21st** of each month will be obtained from Meteorology Database **(2000)** for Baghdad City according to the following table ( **2** ):

The peak noontime Solar Irradiance (**$I_{noon}$ (W / m$^2$)** ) for **21$^{st}$** of each month will also be obtained from Meteorology Database **(2000)** for Baghdad City as shown in the following table ( **3** ) and figure ( **7** ) which show the estimated values according to equation **( 6 )** for some months:

The collector's mass flow rate**(** $m_{co}$ **)**, will be considered water instead of glycol. The optimum fluid flow rates are usually in the range of **( 0.006 to 0.014 kg/sec.m$^2$)** (ref. 7), we will use here for our calculated area **(0.0065 kg/sec.m$^2$)** to have a total flow rate of **(0.67 kg/sec)**.

The pump power **(** $P$ **)** is supposed to be **( 500 W )**, **(** $DT$ **)** the driving force temperature difference**(3 $^o$C)** and the Initial Storage Water Tank **(** $T_i$ **)** to be equal to Feeding temp. **(**$T_{feed}$ **)**, **(**$Dt$ = **14 hr )**, the fraction **(** $f$ **= 0.1)** and **(** $T_{i-off}$ **)** to be equal to **(** $T_{st}$ **)** at the sunset time. Substituting these parameters in equation **( 9 )** for August, will yield :

$$T_{st} = 37.73 e^{-0.274t} + 37.43\left(1 - e^{-0.274t}\right) + 722\left\{0.33\left(e^{-0.274t} - \cos\left(\frac{\pi . t}{14}\right)\right) + 0.04 \sin\left(\frac{\pi . t}{14}\right)\right\}$$

Equation **( 11 )** becomes after substituting for **(** $f$ = 0.1 **)**:

$$T_{st-off} = T_{i-off} \cdot e^{-1.1t} + 37.73\left(1 - e^{-1.1t}\right)$$

## 6. Results & Discussion

The analysis for this research shows the possibility to predict the Storage Tank Water temperature **(** $T_{st}$ **)** during any day in the year and the succession days for any period during the year, the data required for this research mainly is the global or total incident solar radiation at Noon ( $I_{noon}$ ) for each day in the year and the average ambient temperature **(** $T_a$ **)** which can be obtained from the Meteorology Database on any location or position on the Earth.

Figure **( 8 )** below shows the Storage Water Tank temperature variation through the day according to the above equations for **21$^{st}$** of August. The figure shows also that the heating time starts at sunrise time at **( 5 O'clock a.m. morning )** and ends at **( 5 O'clock a. m.  morning )** of the next day, and **(** $T_{i-off}$ **)** represents the storage tank temp. **(**$T_{st}$ **)** at sunset time.

It appears clearly that the storage tank temp. for the second day will begin with higher temperature than the initial temperature of the first day of system operation. This means that the storage tank temperature of the next day will be higher than **( 75 $^o$C )** and so on, but it depends mainly on the Solar Radiation during the day which is a parameter of Meteorology variation, sky clearance and day time in the year is clearly shown in figure ( **9** ). It is seen that solar energy decreases during the summer months of May, June & July which is not an indication that April is the shiniest month because our calculation is focused on the **21$^{st}$** of each month and more important factor is temperature difference between collector inlet temperature ( $T_{ci}$ ) and the ambient temperature ( $T_a$ ) which is the main parameter to make the collector less effective when ( $T_{ci}$ ) increases to cause more heat loss from the collector to take place.

Figure ( **9** ) below shows the Solar Energy **(** $Q_{solar}$ **)** gained during the daylight period, the Added Energy **(** $Q_{added}$ **)** adds by the Auxiliary Heater when the outlet storage tank water temp. **(** $T_{st}$ **)** is lower than the reference temp. **(** $T_{ref}$ **)** and the Total Required Energy **(** $Q_{total}$ **)** in Mega Joules for **21**$^{st}$ complete day of each month during the year. The system should have sensors that allow to determine the inlet water temp. to the Auxiliary Heater to add only the amount of heat needed.

The percent of the Solar energy or Added energy to the Total required energy for **21**$^{st}$ of each month is shown in figure **( 10 )** below, it sees that even with our estimation to design a water heating system to match heat demanding we obtain lower effective system which about **%85**, but more precise calculation may yield to a better results if an accumulative calculation for succession days or months is done or performed with software programming.

Figure **( 11 )** below shows the Storage Tank Temp. variation during the **21**$^{st}$ of some specific months to compare between them and see how the temperatures increase as the Solar Insolation coming from sun increases for summer season months. It appears that the storage tank water temp. **(** $T_{st}$ **)** becomes higher than the reference temp. **(** $T_{ref}$ **)** for May, June & July, thus the existence of a controller device is essential to store this heat and to be used later. This case can be well understood or apparently visible in figure ( **12** ) which shows that the solar water tank temp. will increase to jump over **( 60 $^{o}$C )** at about **10 O'clock A. M to about 7 O'clock P.M**. The backup stored tank can be used with a controller programmed device to overcome this problem.To study the effect of the collector's area. Let as see how the Storage temperature varies as the collector's area changes to lower value says to be **(** $A_c$ **= 60 m$^2$ )**. The calculation was done for **21**$^{st}$ of January. It is seen from figure ( **13** ) that the storage tank water temperature decreased as the collector's area is decreased which is a fact to say because collector area plays as a main factor solar energy collecting. But another case appears clearly that during the off time the storage tank temperature for less collector area varies slower than collector area with higher area because the heat exchange between the storage tank water temperature and feeding temperature is decreased as the temperature difference between them is decreased.

### 7. References

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**Table (1) The Avg. monthly ambient temp. & Feeding temp.**

| Month No. ( n ) | Jan. 1 | Feb. 2 | Mar. 3 | Apr. 4 | May 5 | Jun. 6 | Jul. 7 | Aug. 8 | Sep. 9 | Oct. 10 | Nov. 11 | Dec. 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Avg. monthly ambient temp. ($^oC$) | 9.28 | 11.31 | 16.05 | 25.42 | 29.25 | 33.15 | 37.73 | 36.25 | 30.62 | 22.77 | 15.31 | 11.58 |
| $T_{feed}$ ($^oC$) | 11.19 | 9.28 | 11.19 | 16.39 | 23.51 | 30.62 | 35.82 | 37.73 | 35.82 | 30.62 | 23.51 | 16.39 |

**Table (2) The Avg. daylight ambient temp. for 21$^{st}$ of each month.**

| Month No. ( n ) | Jan. 1 | Feb. 2 | Mar. 3 | Apr. 4 | May 5 | Jun. 6 | Jul. 7 | Aug. 8 | Sep. 9 | Oct. 10 | Nov. 11 | Dec. 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ( $T_a$ ) Avg. daylight ambient temp. ( $^oC$ ) | 11.83 | 15.00 | 23.73 | 31.00 | 32.30 | 34.40 | 41.56 | 39.36 | 31.30 | 27.60 | 16.72 | 13.15 |

**Table (3) The Peak Noon Solar Irradiance for 21$^{st}$ of each month.**

| Month No. ( n ) | Jan. 1 | Feb. 2 | Mar. 3 | Apr. 4 | May 5 | Jun. 6 | Jul. 7 | Aug. 8 | Sep. 9 | Oct. 10 | Nov. 11 | Dec. 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $I_{noon}$ Peak noon Soalr Irradiance ($W/m^2$) | 493 | 595 | 675 | 720 | 760 | 732 | 684 | 722 | 629 | 594 | 455 | 408 |

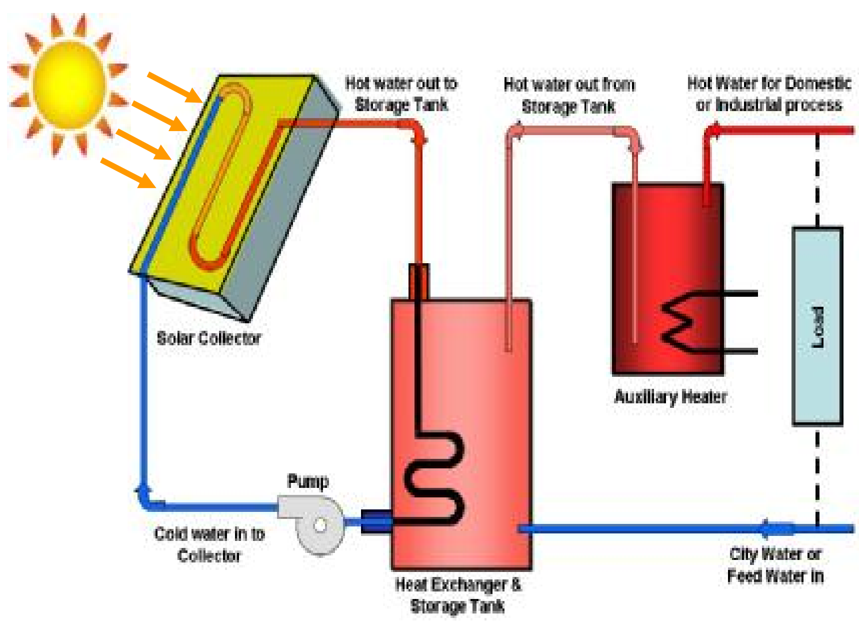


**Figure (1) Schematic diagram of a Solar Thermal Hot Water System.**

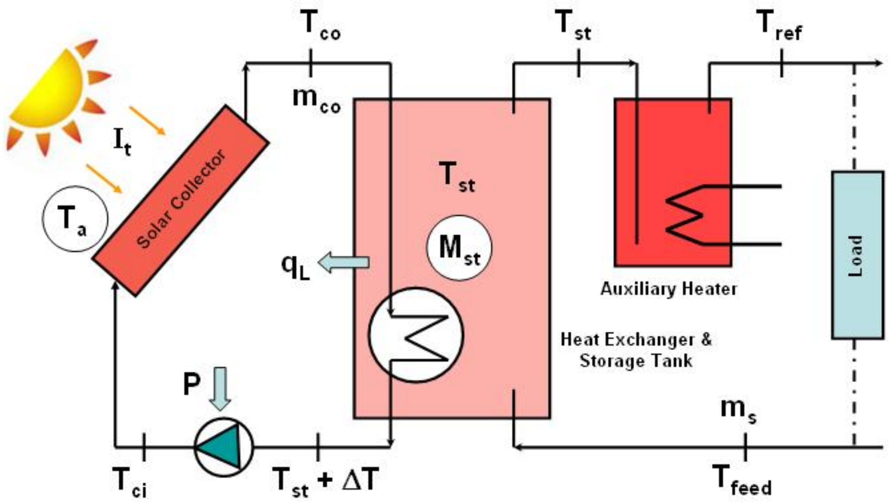


**Figure (2) Schematic diagram of simplified Solar Water Heating System.**

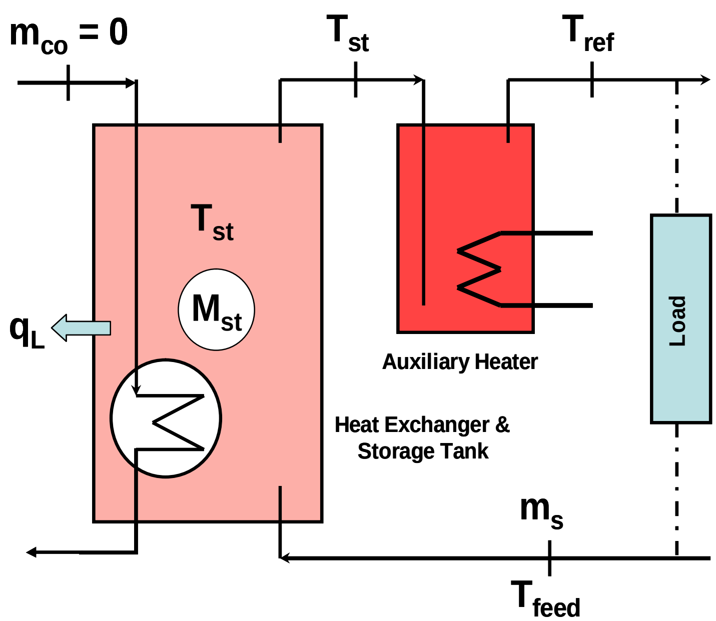


**Figure (3) Schematic diagram for storage tank after sun set.**

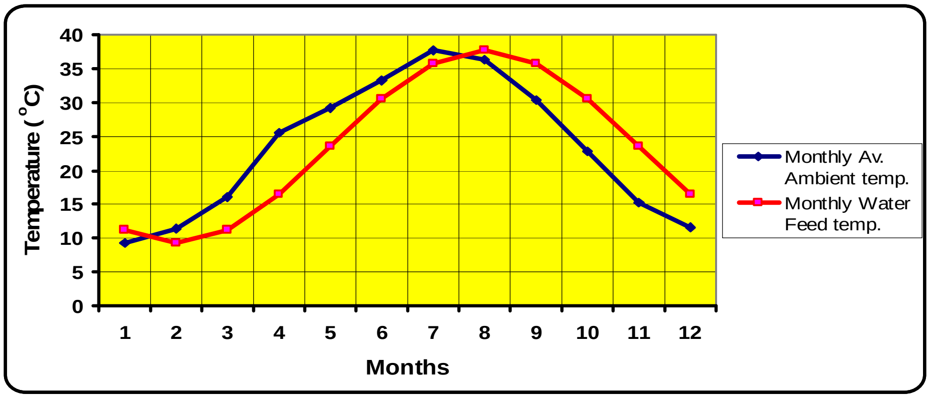


**Figure (4) The Avg. monthly ambient temp. & Feeding water temp.**

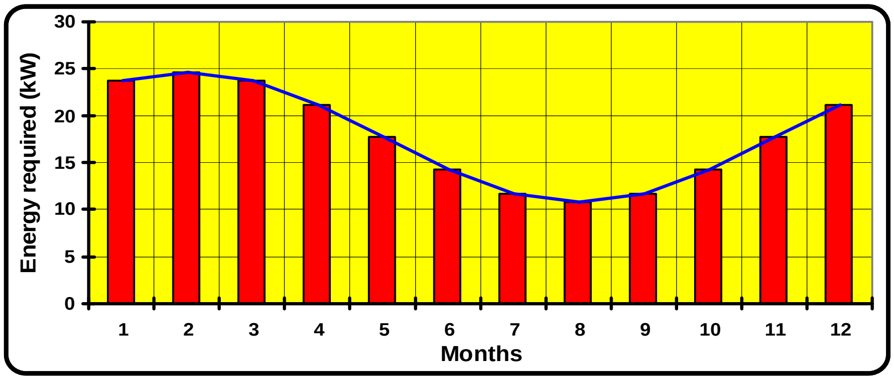


**Figure (5) The Load energy required for each month**

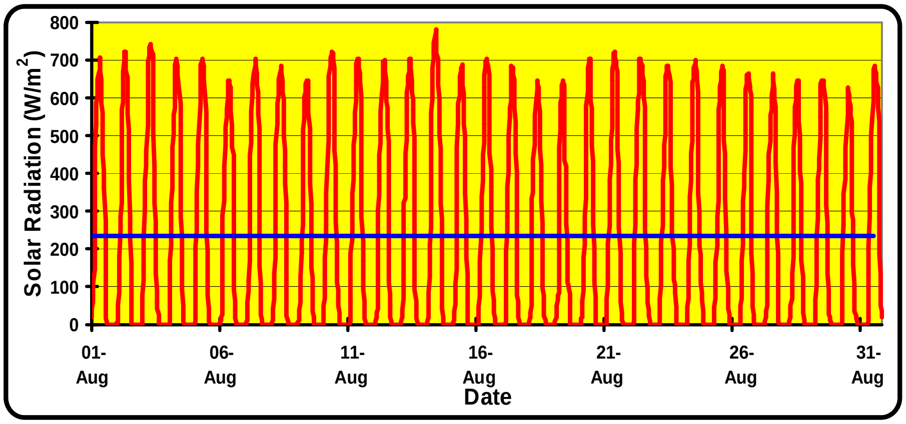


**Figure (6) The Daily variation in Solar Insolation for August month.**

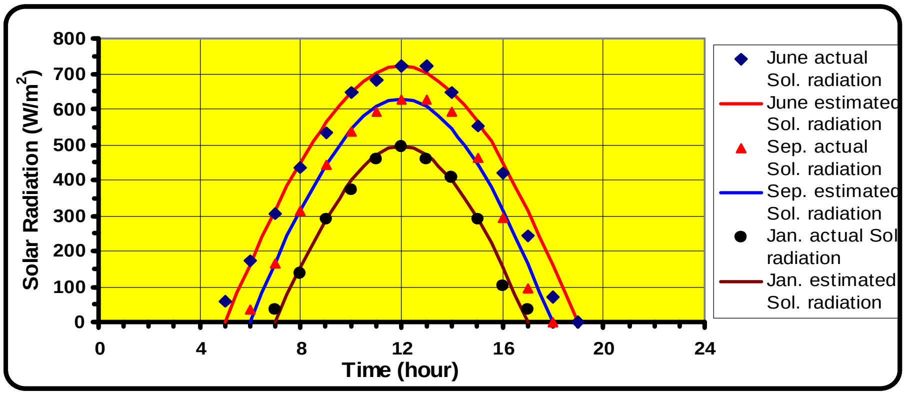


Figure (7) The Estimated and Actual Sol. Radiation for 21st of some months.

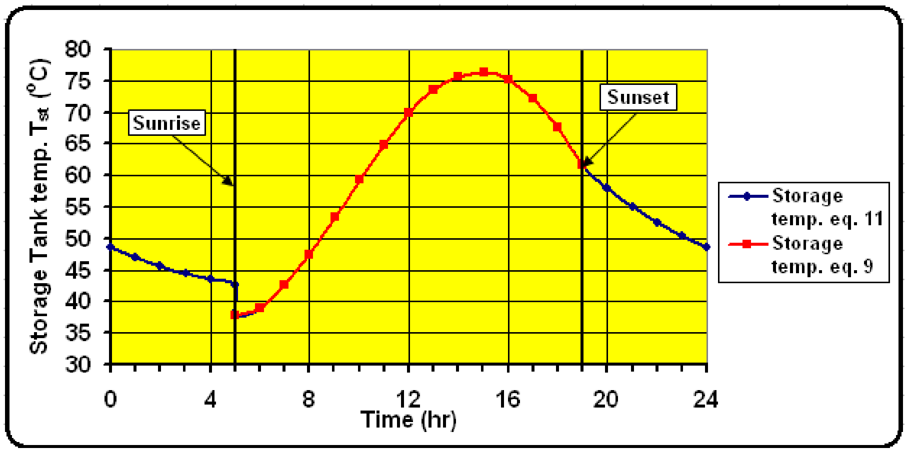


Figure (8) Storage Tank Temp. change during 24 hour of 21st of August month.

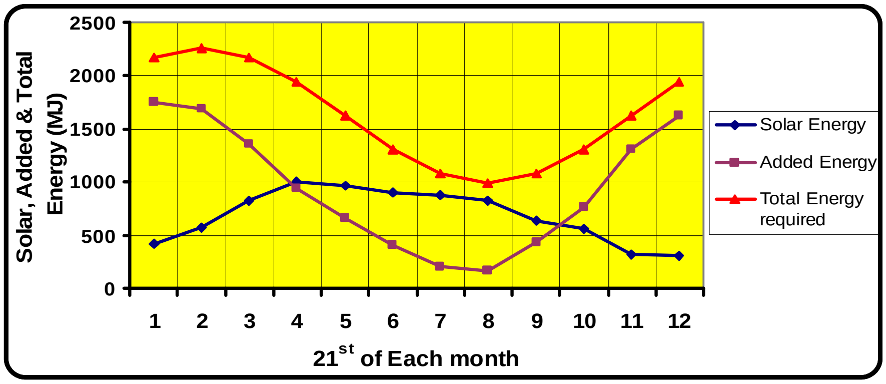


Figure (9) Solar, Added and Total Required Energy for 21st of each month.

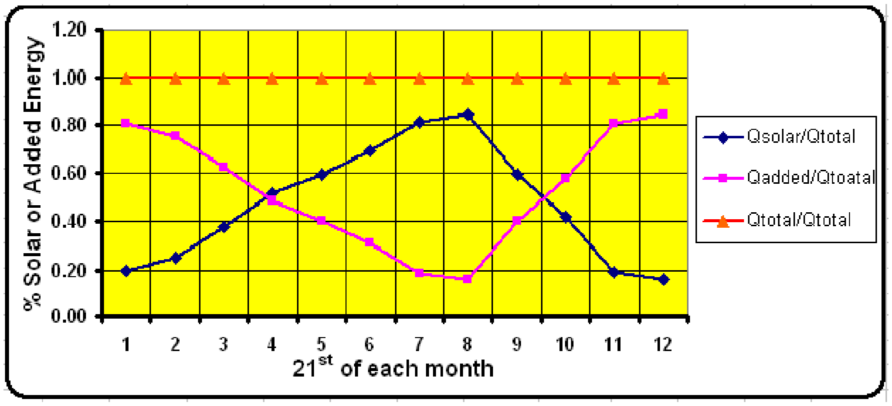


**Figure (10)The % of Solar Energy & Added Energy to Total for 21st of each month.**

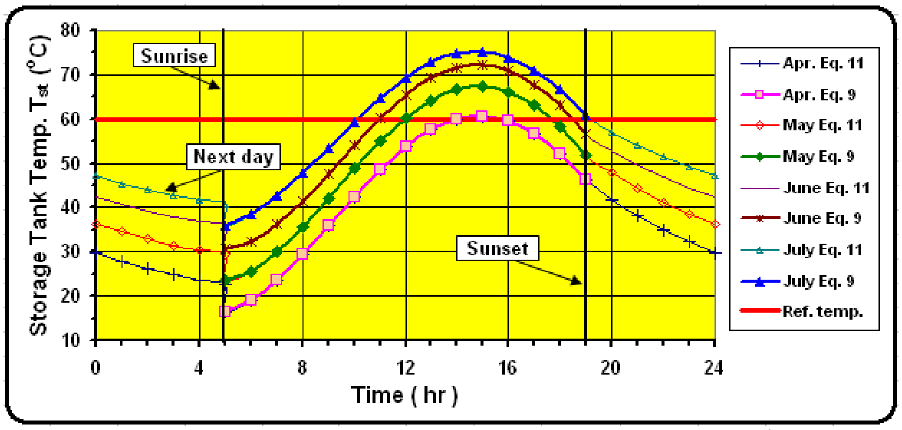


**Figure (11) Storage Tank Temp. change during 24 hour of 21st of some months.**

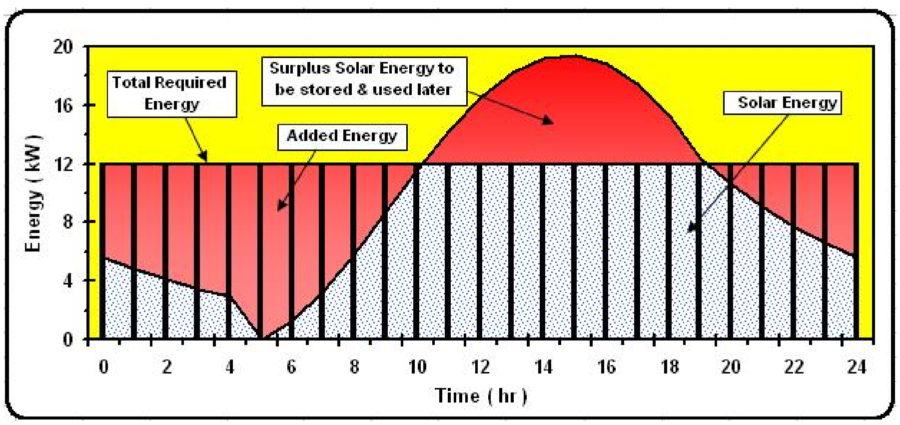


**Figure (12) The Instantaneous Solar, Added Energy & the Surplus Solar Energy to be stored during the 21st day of July.**

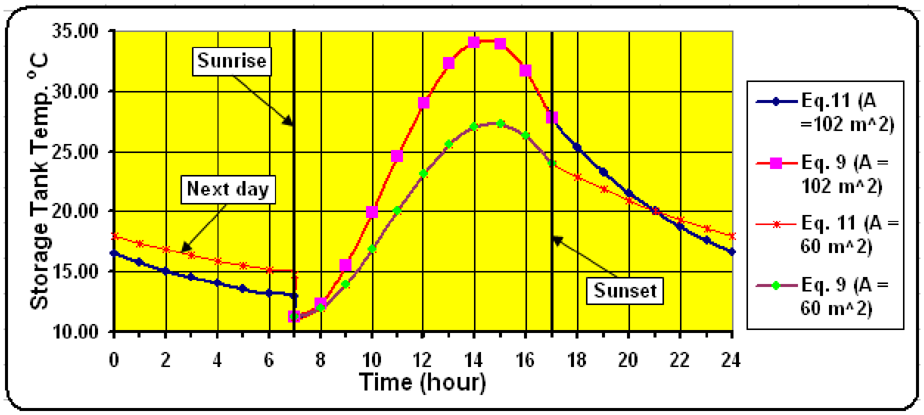


**Figure (13) Storage Tank Water Temperature changes during 24 hour of 21 st of January with different collector's area.**