Conference Proceedings

EuroSun 2014
Aix-les-Bains (France), 16 - 19 September 2014

Long-term Performance Prediction for Domestic Solar Water Heating Systems

José Luis Duomarco

duomarco@adinet.com.uy

A.I.U. Montevideo, Uruguay

Abstract

New software has been developed, adapted to International Standard ISO 9459-2, in which the daily solar domestic hot water (SDHW) system operation is modeled with a heat-limited consumption scheme, fixed by a nominal temperature (Tdn), and a daily nominal hot water volume production (Vdn). Solar energy is traced to its end forms; overheating in summer months, remaining in storage to be used the next day, lost through storage tank surface and drawn-off in the useful hot water. Auxiliary heat to comply with nominal settings is also calculated. For commercial reasons it is becoming more and more necessary to have an effective way of classifying SDHW systems. Our proposal is to use as figure of merit, the rate between the hot water produced in one year and the auxiliary heat needed, (L/kWh), calculated when the daily extraction is 2/3 of the storage volume and the temperature is Tdn = 60°C. The draw-back of such a procedure results from observing that the value obtained is site-dependent. An alternative classification way is presented, based on a non-dimensional number that is totally site-independent.

Key-words: solar domestic hot water systems; international standards; solar systems classification

1. Introduction

Which is the best solar collector? The question has not an easy answer, although it is persistently made by newcomers.

The cost of the system is the first thing to consider. The durability and quality of materials should be related to cost and are quite visible at a glance. The standard tests related to quality are well established and are similar to other outdoor equipment tests (ISO 9806-2, 1995).

Nevertheless, calculation of energy delivered by the system over its lifetime has had several approaches. The Solar Energy Laboratory of the University of Wisconsin, UW-SEL, has developed a modular method, where each module is tested separately. The parameters obtained are then fed into especial software where annual performance is calculated. The f-chart and TRNSYS, works on these trends (Duffie & Beckman, 1991). The solar Collector and System Testing Group, CSTG, has followed a track quite different because no reference is made to components parameters (ISO 9459-2, 1995). The system is characterized from the start as a black box with input-output parameters that are determined by an all-day test. Maybe the most important difference between the two methods is in how the store stratification event is handled. In the method of UW-SEL several analytical models are developed while in the method of CSTG, stratification is already taken into account in the experimental results.

The International Standard ISO 9459-2: 1995 applies to SDHW systems operated without auxiliary boosting and for an evening draw-off. The test procedures are applicable only to systems of 0.6 m^3 of solar storage capacity or less. Software that allows a volume-limited and a temperature-limited demand is given by the standard. We have developed software, in which the daily demand is modeled with a heat-limited consumption scheme fixed by a nominal temperature and a nominal hot water production.

Selection and/or peer review under responsibility of EuroSun2014 Scientific Committee
doi:10.18086/eurosun.2014.03.07 Available at http://proceedings.ises.org

Table 1 Nomenclature: Sub-index i identifies the year´s day

A_c	Collector aperture surface	m^2	A_S	Storage tank surface	m^2
a1	Harness coefficient 1	m^2	a2	Harness coefficient 2	J/K/d
a3	Harness coefficient 3	J/d	G_{Ti}	Solar daily irradiation on collector aperture.	$J/m^2/d$
$f(V_d)$	Test normalized draw–off temperature profile	-	$g(V_d)$	Mixture normalized draw–off temperature profile,	-
Q_{dSi}	Sensible heat in water withdrawn from the system, with mixture.	J/d	Q_{dTi}	Sensible heat in water withdrawn from the system, without mixture.	J/d
Q_{losti}	Heat loss from storage´s surface	J/d	Q_{Ri}	Remains of heat in storage after water is withdrawn.	J/d
Q_{Si}	Sensible heat in storage before draw-off	J/d	Q_{Ti}	Solar energy harnessed by collector.	J/d
Q_i	Available heat in system	J/d	Q_{auxi}	$Q_{aux}^{(1)}+Q_{aux}^{(2)}+Q_{aux}^{(3)}$ auxiliary heat	J/d
$Q^{(1)}_{auxi}$	auxiliary heat Q_{dn} -complementary	J/d	$Q^{(2)}_{auxi}$	auxiliary heat V_{dn} -complementary	J/d
$Q^{(3)}_{auxi}$	auxiliary heat T_{dn} –complementary	J/d	Q_{di}	Drawn-off heat	J/d
Q_{dni}	Nominal draw-off heat	J/d	T_{aamin}	Minimum ambient Temperature in the year	°C
T_{aamax}	Maximum ambient temperature in the year	°C	T_{ai}	$(T_{amin}+T_{amax})/2$ Day´s mean ambient temperature	°C
T_{Si}	Storage temperature before water is withdrawn	°C	T_{maini}	Daily temperature of cold water supply; reference for sensible heats.	°C
T_{di}	Water draw-off temperature.	ºC	T_{Ii}	Storage temperature after water is withdrawn	ºC
T_{dn}	Nominal draw-off temperature.	60°C	U_S	Storage tank heat loss coefficient	W/K
V_S	Storage volume	L	V_{dn}	Nominal draw-off volume	L/d
V_{di}	Water volume withdrawn	L/d	r_i	Overheating factor	-
Δt	time interval	s	x_i	$(T_{Si}-T_{ai}-a3/a2)/G_T$ Reduced temperature	$(Km^2d)/J$
δ_0	a1 / Ac Optical efficiency	-	δ_1	a2 / Ac Collector loss	$J/(Km^2d)$
ρ_ω	Water density	1 kg/L	c_{pw}	Specific heat capacity of water.	4.1868 kJ/(kgK)
q_{auxi}	Mean annual auxiliary heat needed to produce a unit volume of hot water in its nominal ratings, when solar energy is available.	J/L	q_{dn}	Maximum qaux when no solar energy is available	J/L
Q_{ohi}	Overheat	J/d			

For commercial reasons it is becoming more and more necessary to have an effective way of classifying SDHW systems, from an energy preserving point of view. Our proposal is to use as figure of merit, a long-term performance prediction, given as the rate between the hot water produced and the auxiliary heat used in one year (L/kWh), calculated when the daily extraction is 2/3 of the storage volume and the temperature is 60°C. The highest its value, the better; more hot water is produced with the unit of auxiliary energy. The draw-back of such a procedure results from observing that the value obtained is site-dependent. One would like to be able to classify SDHW systems in an intrinsic way, only dependent on the systems characteristics. An alternative classification procedure is presented, based on a non-dimensional number description of the SDHW system that is totally site-independent.

2. Method

In the ISO 9459-2 standard, the system characterization is obtained from three tests and an algorithm for evaluating the long-term-performance-prediction (LTPP):

- Draw-off profile test.

This temperature profile, obtained during the extraction of three times the storage tank volume of water, characterizes the behavior of the storage tank, when the hot water inside, mixes with the cold water coming in from mains. Two different functions f(V) and g(V) are used. The first is obtained based on a draw-off profile performed at the end of each test-day and the second is based on a separate test determining the mixing draw-off profile when the tank has an initial uniform temperature, without stratification. The formulas (1) and (2) give the analytical definition of these functions.

- Input-output diagram

The daily behavior of the system is characterized by a linear model defined in formulas (8) and (8'). The parameters are obtained by least squares fitting of the following daily test results:

• $Q_T = Q_{T3Vs}$	- sensible energy contained in the three times the tank volume of water, drawn-off in the daily test
• $T_S = T_{main}$	- cold water temperature during the daily test
• T_a & G_T	- ambient temperature and solar irradiation on collector aperture, during the daily test

- Store overnight loss coefficient

The store heat loss coefficient is obtained in an independent test, where the storage tank is left to cool down overnight. Equation (3) is used.

- LTPP

The long-term performance prediction is calculated by software given in the standard. It includes two load patterns:

- ***Load pattern 1***, determined by the volume of daily hot water consumption,

- ***Load pattern 2***, determined by a minimum useful temperature limit for the hot water consumption. When the outlet temperature is lower than this minimum value, no water is extracted from the store.

- New LTPP.

New software has been developed, not included in the standard, with a different load pattern:

- ***Load pattern 3,*** modeled for a nominal temperature and a nominal hot water volume production, both constant during the year. According to the daily climate conditions and daily hot water extraction, the draw-off temperature and draw-off volume may be under or above the nominal values. If overheating is present, the excess energy over the nominal is calculated and discarded. If solar heating is under the nominal value, the auxiliary heat necessary to reach nominal settings is calculated. The calculation is extended only to 365 days assuming an annual periodicity, although it could be extended further, if longer daily meteorological series were available or synthetic series were used. The algorithm is formulated in the appendix A, equations 1 – 22 with variables defined in the Table 1.

3. Application to Montevideo

A case study has been conducted on system 5 and system 8 as if they were operated in the city of Montevideo, located 34°53' South latitude and 56°09' West longitude, with ***load pattern 3***. The climate data used was obtained from project "Surface Meteorology and Solar Energy" (NASA, 2010). Simultaneous daily global solar radiation on horizontal surface, maximum and minimum temperature series for year 2010, were used in the simulation. The typical data of System 5 and System 8 was obtained from work by V. Belessiotis & D. Harambopoulos,(1993) and are listed in Table 2 and shown in Fig. 1 and Fig. 2. Energy monthly simulation results, given in J/d, are shown in Fig. 3, for system 5. The volume of water extracted each day is two thirds of the storage volume and its temperature is 60 °C, constant for all days of the year. Solar energy is traced to its end forms; overheating in summer months, remaining in storage to be used the next day, lost through storage tank surface and drawn-off in the useful hot water. Auxiliary heat, from another energy source, to comply with nominal settings is also calculated.

4. Solar domestic hot water systems classification

Several procedures have been developed to classify SDHW systems, based in the annual solar energy captured, with a "labeling" purpose, in a commercial context (FSEC, 2002) (INMETRO, 2012). It seems as if the basic idea that solar energy is "free" is sometimes forgotten! Solar energy is used with the purpose of replacing the costly auxiliary energy, whatever its origin. For this reason, another way of comparing SDHW systems would be, to use the amount of auxiliary energy required to produce a unit volume of hot water or the volume produced by the unit of auxiliary energy; the best system being the one with its lowest kWh / L or highest L /kWh values. It might be thought that the solar energy method and the auxiliary method give complementary values, but for winter significant climates, summer overheating may occur, and some solar energy may be discarded.

Table 2: Parameters and experimental results from: "Testing solar water heating systems in Athens, Greece" by V. Belessiotis and D. Haralambopoulos, Solar Energy 50, No. 2, pp167-177, (1993)

System N°	a1 (m^2)	a2 (MJ / K / d)	a3 (MJ / d)	Ac (m^2)	Vs (L)	ls (length) (m)	Ds(diameter) (m)
5	1,58	0,45	-1,37	3,41	200	1,67	0,39
8	0,96	0,47	-1,37	2,05	160	1,34	0,39
System N°	δo=a1/Ac	$\delta 1$=a2/Ac ($MJ/K/m^2/d$)	$\delta 1$=a2/Ac ($W/K/m^2$)	a3/a2 (K)	As (m^2)	Us (W/K)	U_{SC} (W/K)
5	0,4633	0,1320	1,5274	-3,0444	2,2902	2,6	2,93
8	0,4683	0,2293	2,6536	-2,9149	1,8799	1,81	1,87
System N°	Number of collectors	Storage Type	Heat exchange type	Operation type	Vdn = 2/3Vs (L)	Tdn (C)	<Qdn> (MJ /d)
5	2	Horizontal	Tube	Thermo-syphon	133	60	15,543
8	1	Horizontal	Double wall	Thermo-syphon	107	60	10,596

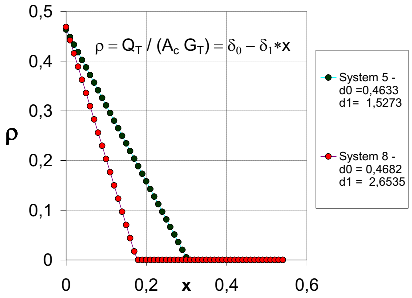

Fig. 1 Input-output diagram obtained from work by (V. Belessiotis & D. Harambopoulos, 1993*)*. The area below the curve is proportional to $\delta o * \delta o/(2 * \delta 1)$. System 5 has more area than System 8. This area increases with decreasing value of δ_1 related to a decreasing heat loss from the system.

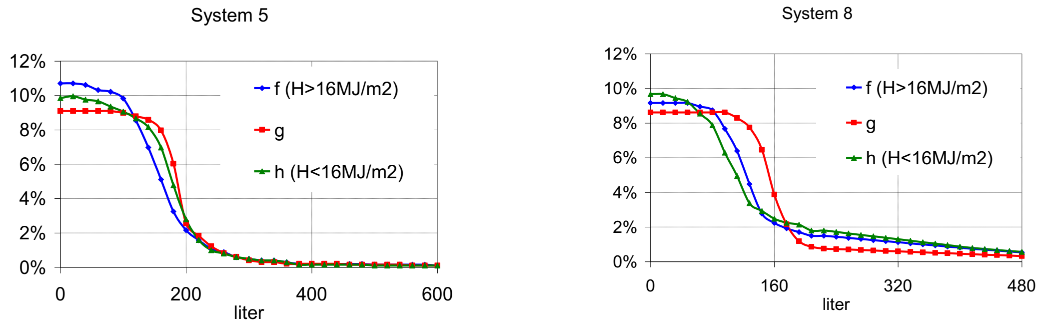

Fig.2 Normalized stratified draw-off profiles (f, h) and mixed draw-off profiles g , for systems 5 and 8, obtained from work by (V.Belessiotis & D. Harambopoulos, 1993)

5. Site-dependent figure of merit

In Fig. 4 and Fig. 5 the ratio (y) of the mean annual auxiliary heat needed to produce a unit volume of hot water in its nominal ratings, when solar energy is available (q_{aux}), to the same item, when the solar energy is not available (q_{dn}), is shown as function of the ratio (x) of the constant daily volume of hot water extracted (V_{dn}) to the storage volume (V_S). In Fig. 4, System 8 is tested in several cities with different climates, Belo Horizonte, Salto, Montevideo, Edinburgh and Punta Arenas. For an extraction of Vdn = Vs/4, cold climate cities begin with y = 60% while mild and warm climate cities begin with y values between 5 % and 20 %. For an extraction, greater than the storage volume (V_S) all 5 functions asymptotically get near to 100%, because an increasing volume of cold water is coming in, for a fixed amount of captured solar heat. In Fig. 5, System 5 and System 8 are compared in the same place, Montevideo. For an extracted volume V_{dn} less than the storage volume V_S, System 5 leads System 8, needing less auxiliary energy to heat up one liter of water. In the trend of classifying solar collector systems with only one number, we selected arbitrarily a constant daily extraction volume $V_{dn} = 2V_S/3$. In Table 3 the ratio of heat per unit volume and volume per unit heat are calculated for System 5 and System 8 in several cities for a daily yield of 2Vs/3; System 5 always takes the lead.

Table 3: Yields in L / kWh and kWh /L

V_{dn} = 2/3Vs	System 5	V_{dn} = 133 L/d	System 8	V_{dn} = 106 L/d
City	q_5^{-1} L / kWh	q_5 kWh / L	q_8^{-1} L / kWh	q_8 kWh / L
Punta Arenas	0,7169	1,3948	0,6416	1,5583
Edinburgh	0,8068	1,2393	0,7169	1,3948
Montevideo	1,7325	0,5771	1,3913	0,7187
Salto	2,0994	0,4763	1,8740	0,5336
Belo Horizonte	3,9727	0,2517	2,1844	0,4577

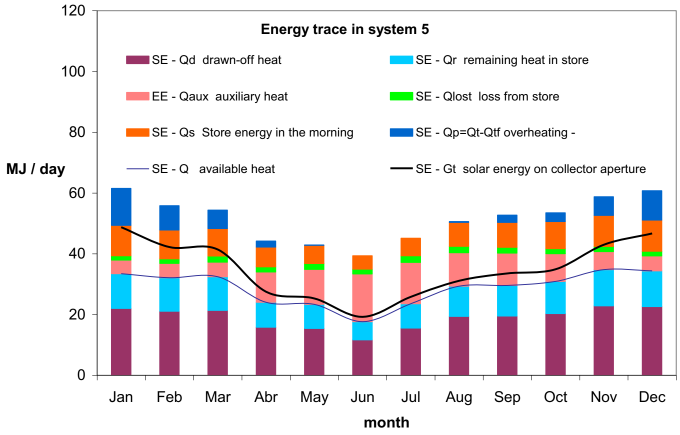

Fig. 3 Annual energy splitting results for simulation with system 5 in Montevideo. Nominal temperature is Tn = 60°C and daily extracted hot water is Vn = 2/3 Vs = 133 L

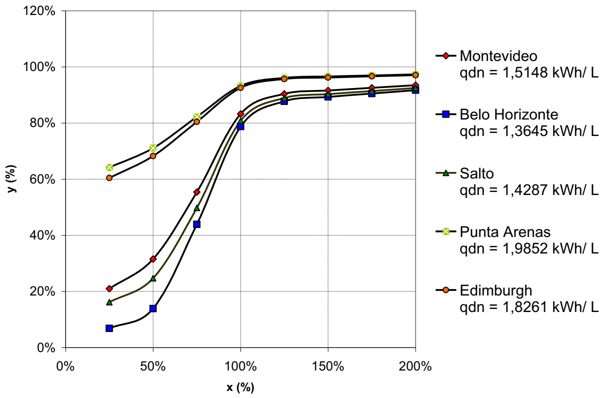

Fig. 4 . Ratio of q_{aux} to q_{dn},(y), as function of the ratio of V_d to V_S, (x), with System 8, for different cities. The climate data used was obtained from project "Surface Meteorology and Solar Energy" (NASA, 2010)

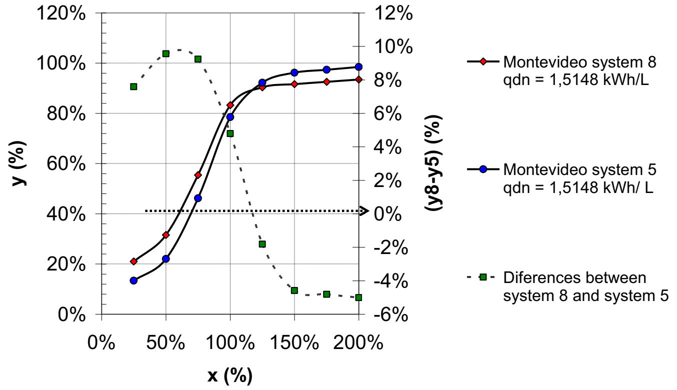

Fig. 5 Ratio of q_{aux} to q_{dn},(y), as function of the ratio of V_d to V_S, (x), for System 5 and System 8 in Montevideo. System 5 is more effective than System 8 in 10% for a volume extraction of $2/3\ V_S$.

Table 4: Site-dependent figure of merit

$q_{dn} = \frac{\sum_{j=1}^{365} Q_{dn_j}}{\sum_{j=1}^{365} V_{dn_j}}$ kWh/L	$q_{aux} = \frac{\sum_{j=1}^{365} Q_{aux_j}}{\sum_{j=1}^{365} V_{dn_j}}$ kWh/L	$q_{aux}^{-1} = \frac{\sum_{j=1}^{365} V_{dn_j}}{\sum_{j=1}^{365} Q_{aux_j}}$ L/kWh	$y = \frac{q_{aux}}{q_{dn}}$	$x = \frac{V_d}{V_S} = \frac{2}{3}$

6. Site-independent figure of merit

In Fig. 4 and Table 3, it is shown how q_{aux} depend on location. One would like to be able to classify solar systems in an intrinsic way, only dependent on the systems characteristics and not on its location. An alternative classification procedure is presented, based on a non-dimensional number γo that increases with quality and is totally site independent. This number increases, with increasing $\delta o * \delta o/(2 * \delta 1)$, related to less heat loss in whole system, as shown in Fig. 1, and with decreasing U_S / A_S, related to less heat loss through storage surface. In Table 5 number γo is defined and calculated for System 5 and System 8.

Table 5: Site-independent non-dimensional figure of merit

	System 5	System 8
$\gamma_0 = 100 * \log_{10}\left[\frac{\delta_0^2 A_S}{2\delta_1 U_S}\left(\frac{G_0}{\Delta T_0}\right)^2\right] = 100 * \log_{10}\left[\frac{a_1^2 A_S}{2a_2 A_c U_S}\left(\frac{G_0}{\Delta T_0}\right)^2\right]$ ΔT_O=100°C G_O=1367 W /m^2	101	89

6. Conclusions

An extension of Standard ISO 9459-2 has been developed with the goal of establishing a new way of classifying SDHW Systems. The software supplied by the Standard is modified to sustain a daily load pattern, based in a nominal temperature and a nominal daily hot water volume production, both constant during the simulated year.

The software makes daily calculations of the following items:
- Discarded energy due to overheating.
- Remaining energies in store after evening draw-off and in the next morning.
- Energy loss through store surface.
- Useful energy in hot water extraction.
- Auxiliary energy necessary to reach nominal settings.

Returning to our initial question -¿ which is the best solar collector?- two answers have been given.

- "The best solar heating water system is the one that produces more hot water per unit of auxiliary heat, or needs less auxiliary heat to produce a unit volume of hot water". The required costly auxiliary energy and the volume of hot water produced in a year are used to define the figures of merit q_{aux} and q_{aux}^{-1} as shown in Table 4. The new software is run with a daily volume extraction equal to two thirds the storage tank volume and temperature equal to 60 °C. From a commercial point of view it has the drawback that it depends on the site where the system is installed.

- "The best solar heating water system is the one with less thermal loses or profits the most from the free solar energy". Two independent loss mechanisms may always be identified: day collector-thermal- loss and night storage-thermal-loss. The figure of merit γ_o, defined in Table 5, is inversely proportional to these two ways of loosing heat. It also has the advantage of being site–independent.

References

V. Belessiotis and D. Harambopoulos, 1993. Testing solar water heating systems in Athens, Greece. Solar Energy 50, No. 2, pp167-177.

B. Bourgues, A. Rabl, M.J. Carvalho & M. Collares-Pereira, 1991. Accuracy of the European solar water heater test procedure. Part 1 & Part 2. Solar Energy, vol. 47 no.1, pp 1-25.

M. J. Carvalho & D. J. Naron, 2000. Comparison of test methods for evaluation of thermal performance of preheat and solar-only factory made systems. Solar Energy, vol 69 (Suppl.) no 1-6, pp. 145-156

Duffie & Beckman,1991. Solar Engineering of Thermal Process. Wiley-Interscience. New York.

J.L. Duomarco, 2012. Predicción del comportamiento de sistemas solares de calentamiento de agua a largo plazo. IV Congresso Brasileiro de Energia Solar, V Conferência Latino Americana da ISES. Sâo Paulo, Brasil

Florida Solar Energy Center (FSEC), 2002. Operation of the Collector Certification Program. FSEC-GP-6-80-Florida.

INMETRO, 2012. Regulamento da qualidade para equipamento de aquecimento solar de agua. Brasil.

ISO 9459-2:1995. Solar heating. Domestic water heating systems- Part 2: Outdoor test methods for system performance prediction of solar-only systems.

ISO 9806-2, 1995. Test Methods for Solar Collectors – Part 2: Qualification Test Procedures.

NASA, 2010. Surface meteorology and Solar Energy. http://eosweb.larc.nasa.gov/sse/

RETScreen, 2004. Solar water heating project analysis. pp. 22-25. Canada

Appendix A

The modified ISO 9459-2 algorithm (J.L. Duomarco, 2012) is synthesized in 7 steps, where sub index i identifies the day in the year:

- Step 0 – Draw-off profile test, mix profile test and store overnight loss coefficient

$$f(V_j) = \frac{\rho_\omega c_{p\omega} \frac{V_S}{10}\left[T_d(V_j) - T_{main}\right]}{\sum_{j=1}^{30} \rho_\omega c_{p\omega} \frac{V_S}{10}\left[T_d(V_j) - T_{main}\right]} \tag{1}$$

$$g(V_j) = \frac{\rho_\omega c_{p\omega} \frac{V_S}{10}\left[T_d(V_j) - T_{main}\right]}{\sum_{j=1}^{30} \rho_\omega c_{p\omega} \frac{V_S}{10}\left[T_d(V_j) - T_{main}\right]} \tag{2}$$

$$U_S = \frac{\rho_\omega c_{p\omega} V_S}{\Delta t} \ln\left[\frac{T_I - T^a_{\min}}{T_F - T^a_{\min}}\right] \tag{3}$$

- Step 1 – Cold water temperature (RETScreen, 2004) and nominal heat withdrawn daily.

$$T_{main\ i} = \frac{\left(T_{aa\max} + T_{aa\min}\right)}{2} + \frac{0.42\ \left(T_{aa\max} - T_{aa\min}\right)}{2} \cos\left(\frac{2\pi(i-51)}{365}\right) \tag{4}$$

$$Q_{dn_i} = V_{dn} \rho_\omega c_{p\omega}\left(T_{dn} - T_{main_i}\right) \tag{5}$$

- Step 2 – Heat available 6 hours after solar noon.

$$T_{S_{i=1}} = T_{main_{i=1}} \tag{6}$$

$$T_{S_{i+1}} = T_{main_i} + \frac{\left(Q_{R_i} - Q_{lost\,i}\right)}{V_s \rho_\omega c_{p\omega}} \tag{7}$$

$$Q_{T_i} = a_1 G_{T_i} + a_2\left(T_{a_i} - T_{S_i}\right) + a_3 \tag{8}$$

$$Q_{T_i} = A_c G_{T_i}\left[\frac{a_1}{A_c} - \frac{a_2}{A_c}\left(\frac{T_{S_i} - T_{a_i} - \frac{a_3}{a_2}}{G_{T_i}}\right)\right] = A_c G_{T_i}\left(\delta_0 - \delta_1 x_i\right) \tag{8'}$$

$$Q_{S_i} = V_S \rho_\omega c_{p\omega}\left(T_{S_i} - T_{main_i}\right) \tag{9}$$

$$Q_i = r_i Q_{T_i} + Q_{S_i} \tag{10}$$

$$Q_{oh_i} = \left(1 - r_i\right) Q_{T_i} \tag{11}$$

- Step 3 – Temperature and heat in volume withdrawn.

$$Q_{dT_i} = Q_{T_i} \int_0^{V_{d\,i}} f(V)\,dV \tag{12}$$

$$Q_{dS_i} = Q_{S_i} \int_0^{V_{d_i}} g(V) dV \tag{13}$$

$$T_{d_i} = T_{main_i} + \frac{r_i Q_{T_i} f\left(V_{d_i}\right) + Q_{S_i} g\left(V_{d_i}\right)}{0.1 V_S \rho_\omega c_{p\omega}} \tag{14}$$

$$Q_{d_i} = r_i Q_{dT_i} + Q_{dS_i} \tag{15}$$

- Step 4 – Summary of the day (i) and contribution for the next day (i+1).

$$Q_{R_i} = Q_{i} - Q_{d_i} \tag{16}$$

$$T_{i_i} = T_{main_i} + \frac{Q_{R_i}}{V_S \rho_\omega c_{p\omega}} \tag{17}$$

$$Q_{lost_i} = V_S \rho_\omega c_{p\omega} \left(T_{i_i} - T^a_{\min_i}\right) \left[1 - \exp\left(-\frac{U_S \Delta t}{V_S \rho_\omega c_{p\omega}}\right)\right] \tag{18}$$

$$Q^{(1)}_{aux_i} = Q_{dn_i} - Q_{d_i} \tag{19}$$

$$Q^{(2)}_{aux_i} = V_{d_i} \rho_\omega c_{p\omega} \left(T_{dn} - T_{d_i}\right) \tag{20}$$

$$Q^{(3)}_{aux_i} = \left(V_{dn} - V_{d_i}\right) \rho_\omega c_{p\omega} \left(T_{dn} - T_{main_i}\right) \tag{21}$$

$$Q_{aux_i} = Q^{(1)}_{aux_i} + Q^{(2)}_{aux_i} + Q^{(3)}_{aux_i} \tag{22}$$

- Step 5 – Increase $Q_{d_i} \uparrow$ by increasing $V_{d_i} \uparrow$ while $Q_{d_i} < Q_{dn_i}$.

  If it results $V_{d_i} > V_{dn}$ or $T_{d_i} < T_{dn}$ $=>$ $V_{d_i} = V_{dn}$

- Step 6 – Decrease $Q_{d_i} \downarrow$ by decreasing $r_i \downarrow$ while $T_{d_i} > T_{dn}$

  Repeat Step 5 and Step 6 until Q_{d_i} is stable.

- Step 7 – Next day. Procedure is repeated beginning in step 1 for day i+1 and continues through all the year.