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CLASSIFICATION OF SOLAR DOMESTIC HOT WATER SYSTEMS

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Abstract

For commercial reasons it is becoming more and more necessary to have an effective way of classifying solar domestic hot water systems. Customers need a quick advice before shopping and impartial information printed on a label may help. Two indexes are defined, the energy factor and the figure of merit, that can serve this purpose. The energy factor is the rate between the volume of 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, (2Vs/3), and the temperature is T_{DN} = 60°C. The figure of merit is the ratio of the energy factor to a theoretical reference yield; in turn, ratio of the total annual volume of hot water produced, at $T_{DN} = 60^o$, to its content in sensible heat. A Transient System Simulation program (TRNSYS) model and new software, (ISO), have been developed on the guidelines of the International Standard ISO 9459-2, as simulation software on which they can be calculated. The draw-back of such procedures result from observing that the values obtained are site-dependent. An alternative classification way is presented, based on a non-dimensional number that is totally site-independent.

Keywords: *solar domestic hot water systems, international standards, solar systems classification*.

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1. Introduction

For commercial reasons it is becoming more and more necessary to have an effective way of classifying solar domestic hot water (SDHW) systems. Customers need a quick advice before shopping and impartial information printed on a label may help.

The qualification test procedures are well established and are of the pass-fail type (ISO 9806-2, 1995). Instead, energy performance information adapts easily to a numeric or eventually to a color scale. At least two simulation procedures have given the raw material for such a scale. 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. The system is characterized from the start as a black-box with input-output parameters that are determined by an all-day test (ISO 9459-2, 1995).

Until now, the main quantity used to evaluate the energetic performances of SDHW systems has been the solar fraction; defined as the percentage of the total load supplied by the sun. Solar fraction values specific to the collector area are also used (FSEC, 2002) (INMETRO, 2012). But this information should not be enough for a customer that wants to use a constant daily volume of hot water, V_D, at a specified temperature, T_D, all through the year . The auxiliary costly energy requirement is very important and should be a part of the energy performance information.

Two indexes, the energy factor (EF) and the figure of merit (FOM) are adequate. The EF is the rate of the

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volume of hot water produced, to the auxiliary heat used in one year (L / kWh), calculated when the only daily evening time extraction is 2/3 of the storage volume ($2V_S/3$), and the temperature is T_{DN} = 60°C. The FOM is the ratio of the EF to a theoretical reference yield (TRY); in turn ratio of the total annual volume of hot water produced, at T_{DN} = 60ºC, to its content in sensible heat or total auxiliary energy not-sun-assisted needed. The higher their values the better, as more hot water is produced with the unit of auxiliary energy.

The T_{DN} = 60ºC reference temperature, has been chosen in behalf of domestic uses.

The $V_{DN}=2V_S/3$ reference volume has been arbitrarily selected with the only restriction of being less than the storage volume V_S. It is shown in figure 3 that extractions greater or equal than V_S, tend to fade out differences between the y values of collectors, due to the cold water intrusion in the tank.

2. Method

Two different simulation procedures are used in the evaluation of the EF and the FOM:

1. ISO simulation in 2.2 (B. Bourgues, *et al*, 1991) (M. J. Carvalho & D. J. Naron, 2000) (J.L. Duomarco, 2015).
2. TRNSYS simulations in 2.3 (TRNSYS,2000)

2.1 Equations defining the EF and the FOM

- The ratio of the total annual volume of hot water produced, at T_{DN} = 60ºC, to the total sun-assisted auxiliary energy, and its inverse, are written as:

$$v_{AUX} = \frac{365\,V_D}{\sum_{i=1}^{365} Q_{AUX,i}} = \frac{1}{q_{AUX}} \qquad \text{(eq. 1)}$$

- The ratio of the total annual volume of hot water produced, at T_{DN} = 60º, to its content in sensible heat, are written as:

$$v_{DN} = \frac{365\,V_D}{\sum_{i=1}^{365} Q_{DN,i}} = \frac{365\,V_D}{\sum_{i=1}^{365} V_D c_{p\omega}\rho_\omega \left(T_{DN} - T_{MAIN,i}\right)} = \frac{1}{q_{DN}} = TRY \qquad \text{(eq. 2)}$$

- The ratios x and y :

$$x = \frac{V_D}{V_S} \qquad \text{(eq.3)}$$

$$y = \frac{q_{AUX}}{q_{DN}} = \frac{v_{DN}}{v_{AUX}} = \frac{\sum_{i=1}^{365} Q_{AUX,i}}{\sum_{i=1}^{365} Q_{DN,i}} \qquad \text{(eq.4)}$$

- The energy factor:

$$EF = v_{AUX} \qquad when \quad V_D = V_{DN} = \frac{2V_S}{3} \qquad \text{(eq. 5)}$$

- The figure of merit:

$$FOM = \frac{v_{AUX}}{v_{DN}} = \frac{EF}{TRY} = \frac{1}{y} \qquad when \quad V_D = V_{DN} = \frac{2V_S}{3} \qquad \text{(eq.6)}$$

2.2 The ISO simulation.

A detailed description of the test method can be found in the text of the standard ISO 9459.2. The system characterization is obtained by the fulfillment of 4 steps*:*

- input-output diagram,
- draw-off temperature profiles,
- store overnight heat loss coefficient,
- long term performance prediction (LTPP).

The calculation details of LTPP include 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.

The new ISO software has been developed with a different load pattern:

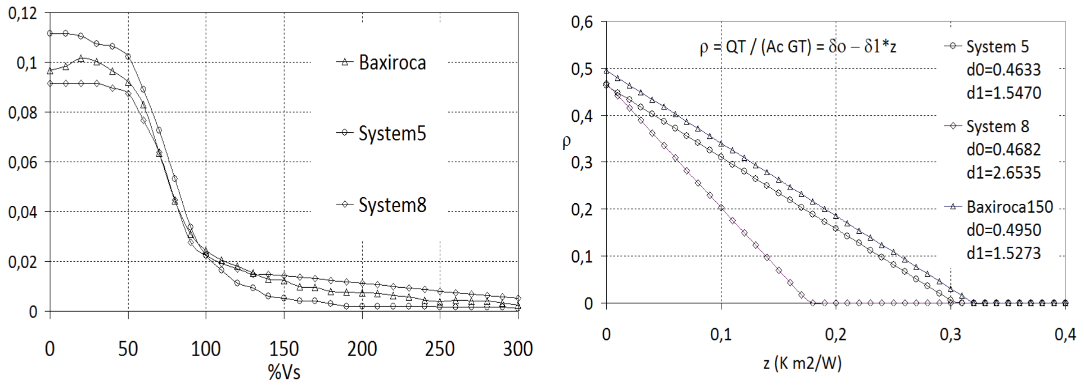
- Load pattern 3: modeled for a nominal temperature and a nominal hot water volume production, both constant during the year, with only one daily draw-off. According to the daily climate conditions and daily hot water demand, the draw-off temperature and draw-off volume may be under or above the nominal 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,
- Case study systems: The performance of three different systems, System5, System8 and Baxiroca, were calculated and compared. The typical data of System 5 and System 8 were obtained from work at the Solar Collectors and Systems Laboratory from the National Research Centre Demokritos (Athens, Greece)(Belessiotis & Harambopoulos, 1993) and similar data for Baxiroca150, from a test report emitted by the "Escuela Superior de Ingenieros" (Seville, Spain) (LCS, 2009).The values are listed in Table 1, the draw-off profiles and the input-output plots are shown in Fig.1. The daily climate data for Belo Horizonte, Salto, Montevideo, Boston, Edinburgh and Punta Arenas were 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.

Table 1 - Experimental results (Belessiotis & Harambopoulos, 1993), (LCS, 2009).

System name	a1 (m^2)	a2 (MJ / K / d)	a3 (MJ / d)	Ac (m^2)	Vs$_{tk}$ (L)	ls$_{tk}$ (length) (m)	Ds$_{tk}$ (diameter) (m)
System 5	1.58	0.45	-1.37	3.41	200	1.67	0.39
System 8	0.96	0.47	-1.37	2.05	160	1.34	0.39
Baxiroca	1	0.27	-0.61	1.92	150	1.25	0.39
System name	δo=a1/Ac	δ1=a2/Ac (MJ/K/m^2/d)	δ1=a2/Ac (W/K/m^2)	a3/a2 (K)	As$_{tk}$ (m^2)	Us$_{tk}$ (W/K)	U$_{SCtk}$ (W/K)
System 5	0.4633	0.1320	1.5274	-3.04	2.2902	2.6	2.93
System 8	0.4683	0.2293	2.6536	-2.91	1.8799	1.81	1.87
Baxiroca	0.5208	0.1406	1.6276	-2.25	1.7773	3.23	-
System name	Number of collectors	Storage Type	Heat exchange	Operation type	V$_{DN}$ = 2/3Vs (L/d)	T$_{DN}$ (°C)	Yield in MVD (L/kWh)
System 5	2	Horizontal	Tube	Thermo-siphon	133	60	56.3
System 8	1	Horizontal	Double wall	Thermo-siphon	107	60	33.6
Baxiroca	1	Horizontal	Tube	Thermo-siphon	100	60	51.1

ISO 9459-2 - eq. (2) - a_1,a_2,a_3 - determined from test results by least-squares fitting methods, Q_T net solar energy gained by the storage tank in the day, T_a ambient air temperature, T_S cold water supply temperature, A_C collector's aperture area, A_S store-tank's surface, V_S store-tank's volume, l_S store-tank's length, D_S store's tank diameter

$$Q_{T_i} = a_1 G_T + a_2 (T_a - T_s) + a_3 = G_T A_C (\delta_0 - \delta_1 z)$$



a) b)

Fig. 1: Normalized draw-off temperature profiles a), and input-output diagram b) ,for Baxiroca, System5 and *System8.*

2.3 The TRNSYS simulation .

A TRNSYS model (TRNSYS, 2000) has been built around component Type 45a and is shown in Fig.3. It requires, 39 parameters, 10 inputs and produces 12 outputs. This component models the thermo-siphon solar collector system. The system consists of a flat-plate solar collector, a stratified storage tank (either vertical or horizontal cylinder) located physically above the collector plate, a check valve to prevent reverse flow, and water as the working fluid. The tank's stratification is modeled with the plug-flow concept.
Global horizontal hourly solar radiation and simultaneous hourly ambient temperature for one year are needed. Two such databases, from Montevideo (Ewenson, 1979) and Salto (LES, 2015) are used. The daily routine consists in evaluating the storage sensible heat at 19h after a day's recollection, making the constant volume draw-off at 20h after fixing its temperature by adding auxiliary heat or discarding overheat and calculating the heat remains in the storage tank. Fig. 2a shows hourly energy variations on May 21 when auxiliary heat is necessary, Fig. 2b similarly for January 5 when overheat is present in the city of Salto and Table 2 lists some parameters, inputs and outputs present with their definitions.

3. Results

In Fig. 4, eight graphs show the index y as function of x.

The reference systems, Baxiroca in 4.1, System5 in 4.2, and System8 in 4.3, are evaluated in the six reference cities, Belo Horizonte, Salto, Montevideo, Boston, Edinburgh and Punta Arenas.

The reference systems, Baxiroca, System5, and System8, are evaluated jointly, with ISO simulation, in Boston 4.4, Salto 4.5, Montevideo 4.6, and with TRNSYS simulation, in Montevideo 4.7, and Salto 4.8

For small values of x, cold climate cities begin with high values of y, around 60%, while mild and warm climate cities begin with y values between 5% and 20%. A null y value stands for no auxiliary heat needed. When draw-off volume V_D, exceeds the storage tank volume V_S, ($V_D>V_S$), all y functions asymptotically get near 100%, or q_{AUX} gets near q_{DN} from below.

When systems are evaluated in the same place, for V_D less than V_S ($V_D<V_S$), System5 leads Baxiroca and Baxiroca leads System8, in the sense that they need 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 Fig. 5, Fig.6 and Table 3, EF and FOM values, are calculated and plotted.

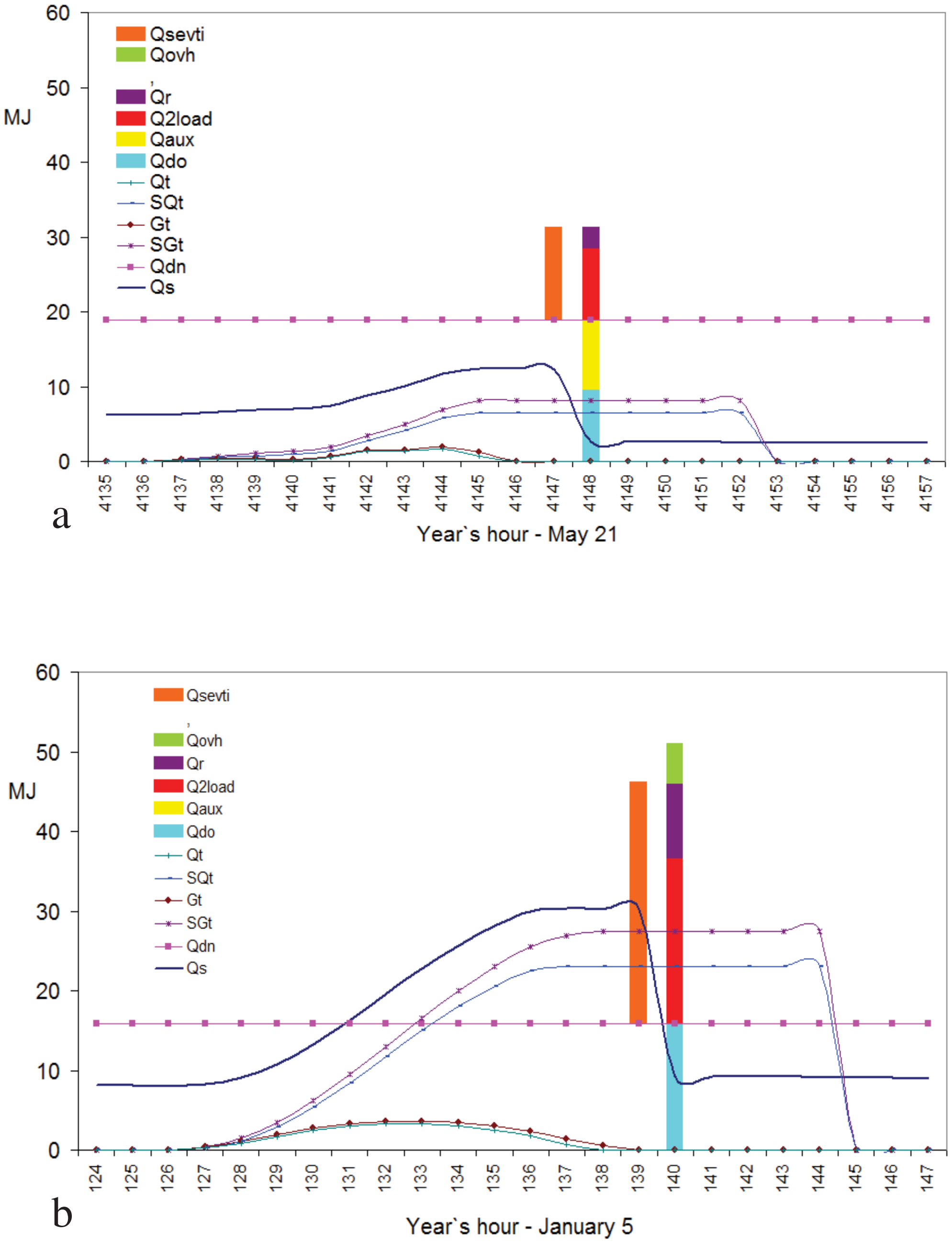


Fig. 2: TRNSYS simulation hourly energy variations in Salto on: a) May21, with auxiliary heat and b) January 5, with overheat

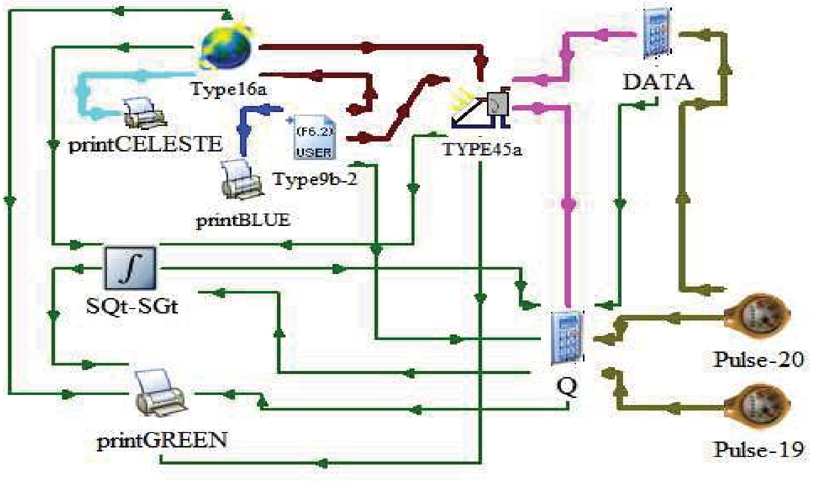


Fig.3: TRNSYS model built around a thermo siphon collector-storage subsystem (Type 45a).

Table 2 - Energy daily transactions in TRNSYS simulation

Hourly events	
Q_{DN}	Daily energy reference settings $Q_{DN.\,i} = V_D.\,4.1868.\,(T_{DN}\text{-}T_{main,\,i})$ - kJ
Q_S	Sensible heat in storage tank - kJ
Q_T	The rate of energy transfer from the heat source to the storage tank - kJ/h
SQ_T	$\int Q_T\,dt$ Accumulated daily energy transfer from the heat source to the storage tank - kJ
G_T	Radiation on the tilted surface (beam + sky diffuse + ground reflected diffuse) - kJ /h m^2
SG_T	$\int G_T\,dt$ Accumulated daily radiation on the tilted surface - kJ/d m^2
Evening time events, at 19h and 20h	
Q_{SEVT}	Sensible heat in storage at evening-time , 19 h - kJ
Q_{2LOAD}	total heat to load, 20h - kJ
Q_{OVH}	Overheat discarded - 20h - kJ
Q_{AUX}	Auxiliary heat to load - 20h - kJ
Q_{DO}	$Q_{2LOAD}\text{-}Q_{OVH}$ Energy removed from the tank to supply the load - 20h - kJ
Q_R	SQ_{SEVT} $\text{-}SQ_{2LOAD}$ - kJ Remains of sensible heat in storage, after draw-off - 20h - kJ

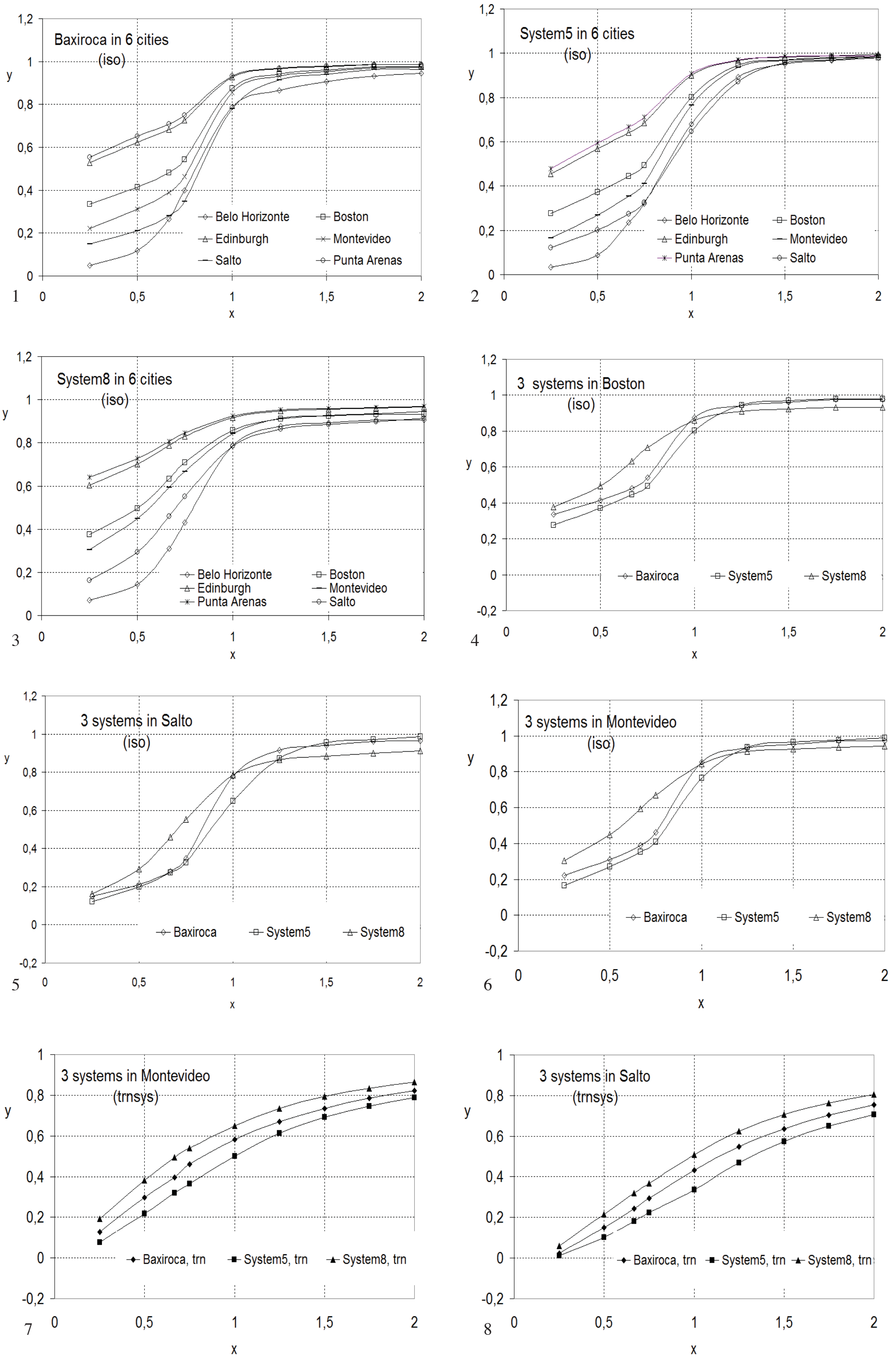


Fig. 4: Ratio y = qaux / qdn as function of ratio x = Vd / Vs, for System 5, System 8 and Baxiroca, using ISO and TRNSYS simulation procedures, in Belo Horizonte, Salto, Montevideo, Boston, Edinburgh and Punta Arenas

Table 3 - Calculation of the EF, FOM and q for System 5, System 8 and Baxiroca by the ISO simulation procedure in Punta Arenas, Edinburgh, Boston, Montevideo, Salto and Belo Horizonte and by the TRNSYS simulation procedure in Montevideo and Salto.

V_{DN} = 2Vs/3 T_{DN} = 60 °C	System 5 V_{DN} = 133.3.. L/d			System 8 V_{DN} = 106.6… L/d			Baxiroca V_{DN} = 100 L/d		
City	EF L/kWh	q_5 kWh /100 L	FOM %	EF L/kWh	q_8 kWh/100L	FOM %	EF L/kWh	q_{bax} kWh/100L	FOM %
iso									
Punta Arenas	22.9	4.354	150	19.0	5.257	124	21.6	4.616	141
Edinburgh	26.0	3.843	156	21.1	4.721	127	24.4	4.093	147
Boston	37.0	2.698	224	26.1	3.828	158	34.3	2.910	208
Montevideo	56.2	1.777	282	33.5	2.979	168	51.1	1.955	256
Salto	77.7	1.285	365	46.3	2.155	218	75.5	1.322	355
Belo Horizonte	94.6	1.056	425	72.1	1.386	324	84.4	1.184	379
trnsys									
Montevideo	62.7	1.595	314	40.3	2.477	202	50.3	1.989	251
Salto	116.6	0.857	547	66.9	1.495	314	87.2	1.146	409

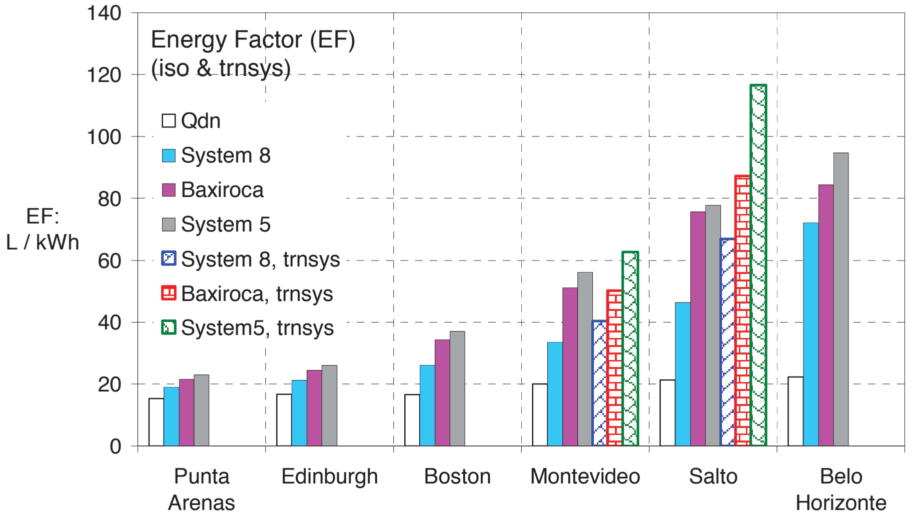


Fig. 5: Theoretical Reference Yield (TRY) and Energy Factor (EF) for 6 different cities, with ISO and TRNSYS simulations.

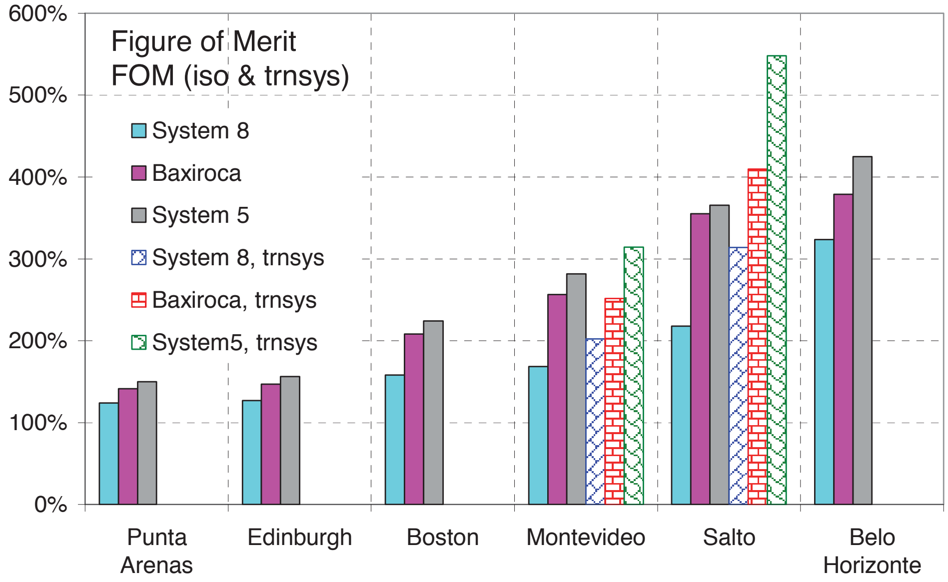


Fig. 6: Figure of Merit FOM for 6 different cities with ISO and TRNSYS procedures.

4. Site-independent figure of merit

From what has been said before, both EF and FOM depend on location. This hinders a universal classification of solar systems based on these indexes. It's desirable to classify SDHW systems in an intrinsic way, only dependent on their characteristics and not on their locations. Commercial confusion is likely to happen when equal indexes may address different SDHW systems measured in different places not properly recorded. An alternative classification procedure has been studied, based on a non-dimensional number γo that gets together all three loss mechanisms,

$$\gamma_0 = 100 * \log_{10}\left[\frac{\delta_0^2}{2\delta_1\lambda_S}\left(\frac{G_0}{\Delta T_0}\right)^2\right] = 100 * \log_{10}\left[\frac{a_1^2 A_S}{2a_2 A_C U_S}\left(\frac{G_0}{\Delta T_0}\right)^2\right]$$

(eq. 7)

where

1. $\lambda_S = U_S / A_S$ with units (W/m^{2}K), characterize the heat loss of the storage tank,
2. $\delta_1 = a_2 / A_C$ with units (W/m^{2}K), characterize the heat loss of the collector,
3. $\delta_0 = a_1 / A_C$ measures the collector's optical efficiency,
4. $\delta_0^2 / (2\delta_1\lambda_S)$ gets together losses and is proportional to the surface under the input-output diagrams,
5. $(G_0 / \Delta T_0)^2$ with Go= 1367 W/m^2 and ΔT = 100 K is a theory-related constant with dimensions,
6. logarithm is taken to smooth-out big variations,
7. calculation of our reference systems is shown in Table 4.

Table 4 - Site-independent non-dimensional figure of merit γ_0

System 5	System 8	Baxiroca
106	90	91

5. Conclusions

The energy factor EF (L/kWh), depends only on end points in the line; hot water production (L), and auxiliary energy to be paid-for (kWh). Free solar energy acts indirectly as a means to improve the EF. The figure of merit FOM is a non-dimensional quantity used to characterize the SDHW system relative to its basic without sun's boosting, alternative.

The simulation program must be specified. Two such simulation programs have been used. TRNSYS models require numerous modules connected with plenty of parameters, acting as input and output data, between them. Sometimes it is cumbersome to set such a simulation. On the other hand, ISO has a black-box-layout, needs fewer experimental results and is easier to use.

EF as FOM are site-dependent and so, meaningless if measuring place is not reported. From an international commerce point of view, it would be helpful to classify SDWH systems in a site-independent way. Three independent loss mechanisms may always be identified: optical efficiency, day collector-thermal-loss and night storage-thermal-loss. Improving these three characteristics, results in a increased non-dimensional γ_0 number with the additional advantage of being site-independent.

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