CHEMICAL ENGINEERING TRANSACTIONS
VOL. 29, 2012
A publication of AIDIC
The Italian Association of Chemical Engineering
Online at: www.aidic.it/cet
Guest Editors: Petar Sabev Varbanov, Hon Loong Lam, Jiří Jaromír Klemeš

ISBN 978-88-95608-20-4; **ISSN** 1974-9791
DOI: 10.3303/CET1229201

Estimating the Energy Savings Potential in a Residential Area of Valparaiso (Chile) by Roof Integrated Unglazed Solar Collectors for Domestic Solar Water Heating

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The aim of this work is the estimation of the potential energy saving in the metropolis zone of Valparaiso (Chile), using Thermal Solar Systems (TSS) integrated to the household roof without glass protection. This selection has two effects, reduce the investment cost and installation, two important factors to consider for the social-economic and physic characteristic of the region in study. The methodology includes the simulation and modeling of the TSS for every single household using the Duffie and Beckman method and with a technical and -economic analysis through the payback period to calculate the overall energy saving performance of the studied area and to determine the characteristics of the household which gives the best performance considering the social-economic factors. The results obtained indicated that there is a theoretical feasibility, from the technical and economical point of view, to implement such technology, concluding that the 56.3 % of the studied households are appropriated to apply the proposed system with lower investment cost, up to 1 million Chilean pesos with a payback period lower than 10 y and a solar fraction between 30 and 65 %.

1. Introduction

Nowadays in Chile as well as in other Latin-American nations does not exist along-term urban planning to deal with the consequence of an eventual future depleting of the fossil fuels within this century and the ambient unsustainable of the all of proposal until today (CONAMA, 2008), (CEPAL, 2009). The cities will require adaptability to new scenarios in which the energy sources will be difficult to access which would generate a notable change in the structure and dynamism of the big cities which must to use new alternative sources of energy for illumination, transport and heating among others services (CEPAL,2009). Considering all these problems, solar energy is the possible candidate to provide the energy required, in particular for countries like Chile which present excellent characteristic for solar radiation in the central zone and the north of the country(Sarmiento, 1995). The use of solar thermal systems for domestic water heating has been widely studied (Mirunalini et al., 2010), however there is very little knowledge about the benefits of implementing such systems on an urban scale. Estimating the solar saving potential of a large-scale geographical region does not only require high amount of computing power but also the availability of a large amount of data, many of them can show large spatial and/or temporal heterogeneity, such as terrain topology, weather, water demand and structural characteristics of housing particularly related to the rooftops. In this sense, many studies have addressed the estimation of the solar potential for water heating considering the rooftop area of households (Ghisi and Ferreira, 2007; Izquierdo, et al., 2008, 2010), but there are not any investigation

Please cite this article as: Carvajal D. and Araya D., (2012), Estimating the energy savings potential in a residential area of valparaiso (Chile) by roof integrated unglazed solar collectors for domestic solar water heating, Chemical Engineering Transactions, 29, 1201-1206

that uses detailed data on geometry, orientation, and inclination of rooftops on a scale of hundreds or thousands of households. This study aims to estimate the potential energy savings in a typical residential area of Valparaiso (Chile), which includes 366 households and 1354 inhabitants, using unglazed domestic hot water solar systems (DHWS) integrated into the roofs. This kind of DHWS was selected for its low investment cost and easy implementation, ideal for the socioeconomic characteristics of the study area. In particular, it discusses the use of galvanized steel roofs used as a solar collector which has a high thermal conductivity and is one of the main building materials in Valparaiso, being used in the 46.5 % (INE, 2002) of the total households due to its low cost and durability. The methodology includes the modelling and simulation of DHWS at the individual household level using the Duffie and Beckman (1991) method and conducting a technical and economic analysis using the simple payback period to determine the overall performance of the study area and to identifying the better household performance considering socioeconomic factors. The used software to model and simulate the solar systems were: PCI Geomantic, ArcGis and Matlab.

2. Materials and methods

Description of the region in study

The study zone is located in an area of 10 ha of the Forestal sector, 33.0447° south latitude, 71.583° west longitude, Viña del Mar, Chile. This area is part of the conurbation called Gran Valparaiso which has a population of more than 824.006 people (INE, 2002) being the third largest conurbation of the country after Greater Santiago (Santiago de Chile). The study zone presents 366 households with a population estimated around 1.354 people (INE, 2002) (around 3.7 inhabitants per household) which are inhabited by families located principally in the socio-economical sector D and E (GSE, Model ADIMARK/INE, 2004) with an average and monthly income around $200.000 (400 USD) (ADIMARK, 2004) which correspond to the 43 % proximately of the Chilean population (GSE, Model ADIMARK/INE, 2004). The study zone, historically have been considered as the most disadvantaged in the consolidation of their urban development (Valdebenito, 2007). These lack of urban planning from the origin of occupation in 1958, in the called “Operaciónsitio” which settled the area with some action called “Tomas” of the land or irregular settlements (Valdebenito, 2002), that today are mostly in process of regularization. The topography of the ground is between 210 - 235 m.s.n.m. and irregular dominated by gradients, 51 % between 0° and 15° and 48.9 % more than 15°, 75 % of the area have slope on the side facing the north followed away by the slope facing the east with a 10.7 % and the west with 9.6 %, presenting just 4 % of a flat surface and finally a 1% with a general exposition due south. All this characteristics are the principal cause of the heterogeneity of the disposition and orientation of the household, in which 40 % of the houses are concentrated in the areas with a slope with restriction to construction. The climate of the area is defined as tempered and warm with winter rains, a prolonged dry season and great cloudiness, determined for the four weather stations, presenting the maximum precipitations in winter, between the months of may and august, the annual average registered is of 300 mm, with the most dried months around 0 mm and most raining around 120 mm, the temperature shift just between 5 and 6 °C among the warm and cold months, while the daily thermal oscillation reach 7 °C in summer and 5 °C in winter, the average monthly temperature is maintained all over the year above 10 °C, with a highly periods of foggy and drizzle (Novoa and Villaseca, 1989), reaching levels around the 80 % of atmosphere humidity.

2.1 GIS method, roof geometry and spatial orientation

The methodology is development in two steps, the first one is to establish for the process of construction of the household in 3D- dimensional space and the second one for the incorporation of all the information to the database of the household model, with the aim to obtain an integrated database SDB+GDB+SEDB (spatial database + geometric database + social-economic database) which is important for the development of the other investigations. Both processes are carried out through the PCI Geomatica Ortoengine and Geographic Systems of Investigation GIS by ArcGis, ArcScene.

2.2 Weather database

The meteorological data consist in weather measurements taken every 10 min of solar direct normal irradiance, solar global horizontal irradiance and diffuse solar irradiance in the horizontal plane, ambient temperature and humidity from 2007 obtained from the laboratory of solar evaluation of Federico Santa Maria Tech University, Chile, Valparaiso station (cerroPlaceres) at 5 km from the studied area. All data was integrated to obtain monthly average hourly instantaneous data to diminish the time for calculation required. There are not data of the albedo for the studied zone for which was used data of urban ambient with similarities like Santiago of Chile with values of albedo of 0.18 for urban ambient. Water temperature database was collected from ESVAL and correspond to the daily values of 2010.

2.3 Design parameters of the system

The collector system is limited by the geometric characteristic, the type of material and coatings used usually in the studied zone. The system design consists basically in two steps: 1. solar collector based on corrugated roofs of standard fabrication, and 2. water storage tanks. The collector consists in a collecting surface conformed by an corrugated steel roof with tubes of cooper dispose in parallel adhered to the roof material (sheet of galvanic steel with zinc) through silicone glue and joined in its extremes by sealing head which are connected at the same time with water storage tanks. Due to the geometry of the roof (waves) the number of tubes for panels is limited for the number of available waves. The external coating of the roof (paint) is diverse depending on the style criteria of every homeowner. The systems of water storage consist of a tank with thermal isolation with adequate capacity to cover household necessity. The operation of the system is quite simple, the water from the public supply network circulate through the tube system of the collector at the moment of more solar radiation allowing the storage of water at high temperature. A flotation valve avoids the overload of water in the tank. An automatic system control open the feeding valve of the system during pre-established times of operation. When the tank is filled, the hot water inside could be used to feed the conventional water boiler (that works with gas or electricity) which rise the temperature to the desired one. The design parameters used were: galvanic sheets of 0.3 mm; roof corrugations wavelength 7.62 cm; useful roof surface 85 %; internal diameter of tubes of 1.445 cm; storage tank of 200 L; material for thermal isolation: mineral wool; thickness of the thermal isolation material for the roof: 5 mm; overall coefficient of heat loss in the tank: 5 W/m^2K. In other hands, it was used as hypothetical hot water demand of 40 °C and 50 L/capita-day.

2.4 Solar radiation model

The overall solar radiation in tilted surfaces is estimated through the sum of the components of the solar radiation direct, diffuse and reflected by the ground, that correspond to the net global radiation incident in a particular surface. The direct radiation over a tilted surface could be easily estimated from the direct normal radiation, knowing the magnitude of the radiation and the position of the sun in the sky. It was used an approximated model for the diffuse radiation which consider the radiation as isotropic in the overall sky, and just depend of the inclination of the surface of the roof without obstruction. The reflected radiation has a similar treatment considering an isotropic behavior depending only from the collector slope. The overall solar radiation in inclined plane (G) can be calculated as:

$$G = G_b + G_d + G_r \tag{1}$$

In which the terms G_b, G_dy G_r correspond to the solar direct radiation, solar diffuse radiation and solar reflected radiation on tilted surfaces.

2.5 Thermal model

Calculations were performed on a period of one year using the monthly average hourly instantaneous data. For the model of heat transfer it was used the Duffie and Beckman method, 1991. The assumptions for this model are the following: 1. the heat transfer in steady state (the capacitive effects of the system are minimal), 2. The flow regime inside the tubes is laminar (Reynolds less than 50), 3. the air movement around the absorber is a consequence only of the wind (It is not considered the natural convection, which is negligible), 4. the temperature gradient through tube wall is negligible, 5. the short and large wave radiation are distributed homogeneity through the system, 6. there are not gradient of temperature inside the tank (tank totally mixed), 7. the heat losses in the lateral and backside part of the collector are negligible. The useful energy gain of the system (Q_u) is given by:

$$Q_u = A \cdot F_r \left[\alpha \cdot G - U \cdot (t_{in} - t_a)\right] \quad (2)$$

Where *A* is the open surface of the collector, F_r the heat removal coefficient of the collector, $\alpha$the sheet absorbance, *U* the overall coefficient of heat losses, t_{in} the initial temperature of the collector and t_a the ambient temperature. In our case $U=h_w+h_r$, where h_w correspond to the coefficient of heat losses by convection, that it is defined by the following equations h_w=5.7+3.8·V_w for wind velocities (V_w, m/s) lesser than 5 m/s and h_w=6.47·$Vw^{0.78}$, for wind velocities higher than 5 m/s. The heat loss coefficient by radiation (h_r) is defined by the expression $h_r=(\varepsilon \cdot \sigma * ((t_p+273.15)^4 - t_{sky}^4)/((t_p+273.15)-(t_a+273.15)))$, in which ε: corresponds to the emissivity of the roof material; σ: constant of Stefan-Boltzman; t_p is the roof temperature (°C), t_{sky}: temperature of the sky (°C) and t_a room temperature (°C)The performance of the SWH can be defined by the value of the solar fraction of the house that corresponds to the fraction of the energy for heating water that it is given by the solar system respect to the energy required without the solar system. To calculate the system costs it can be used two parameters: the initial investment cost and the simple payback period (*PA*) defined as follows:

$$PA = \log\left(\frac{C_i \cdot i}{d_i} + 1\right) / \log(1+i) \quad (3)$$

Where C_i corresponds to the initial investment capital cost, *i* the annual increment of the costs for heating gas and oil and d_i the annual benefits. For annual cost of heating gas was used a value of 3% and current cost of 1.500 pesos/kg.

2.6 Algorithms and computational requirement

The calculation process was developed in MATLAB 7 using an iterative method to calculate the temperature distribution in the system for every household. The program selected the roof side of the house with the best solar exposition in the way of maximize the solar profit. The number of total instruction lines of the program of simulation and post-processing is 3022. The time of calculation necessary for every simulation was 90 min using a computer with double core of 2.26 GHz.

3. Results

Incident solar radiation over the roofs and energy balance

The total solar energy incident over the 366 housings in the studied area during January and July was estimated, concluding that in January there is a peak of approximate 24 MW at 13 h, while in July the maximum intensity is reduced more than the half at 10 MW at 12 h. In January the highest solar radiation was registered for roof sides oriented to northeast and west with values near to 1100 W/m^2 and in July close to 600 W/m^2 for roof sides oriented to northeast.

The results of the numerical model indicate that the output temperature of every thermal solar system at noon varies notably through the year as well as for the difference households for every month. There is a peak of output temperature of the system in January with most of values that oscillate between 49 and 62 °C (represent 70 % of the information) while in July was observed lower temperature with most of the values between 22 and 36 °C, all of these presented in figure 1. The overall behavior is a consequence of the evolution of the solar radiation during all over the year and its effects in the difference conditions of operation of the collector: network water temperature and room temperature. It was registered a notable variation between the water temperature of the network and the room temperature that achieve almost 5 °C between March and June. In this period, the water of the network is mostly at the ambient temperature which is negative for the thermal balance of the system due to the increment of convection and radiation losses.

The evidence of all these mentioned results is reflected in the global efficiency of the system during the year, however the reduction in the efficiency could not be explained only by the increment of the coefficient of heat transference by convection and radiation, but also by the impact of geometric parameters of the collector, that are not linear, as the relation length/width of the collector (l/w), the total energy gained (Q_u), this mean that the two collectors can operate with the same area, orientation, slope and surface coating but with different efficiencies when the (l/w) is different.

Analyzing the distribution of the frequency of households respect to the solar fraction it is observed a high dispersion of the data with a range of values between 27.9 and 57 % with an average near to 44 %. The gain of the solar system respect to overall energy required for hot water is presented in figure 2. The month with the higher solar faction is February due to the high solar radiation and the lesser temperature difference between the water of the red and the demanding temperature (40 °C). The worst month is June due to the reduction of solar radiation and the rise of energy required to heat water as a consequence of the decrease of temperature in the network water.

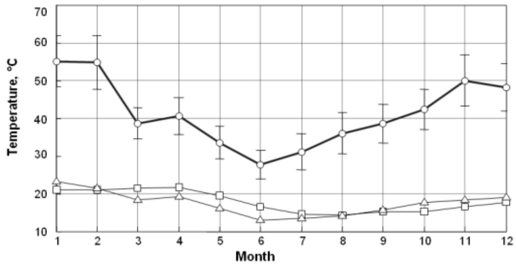

Figure 1. Output temperature of the system at noon. The circles represent the output temperature, squares: the water of the network (average for month); triangles: ambient temperature.

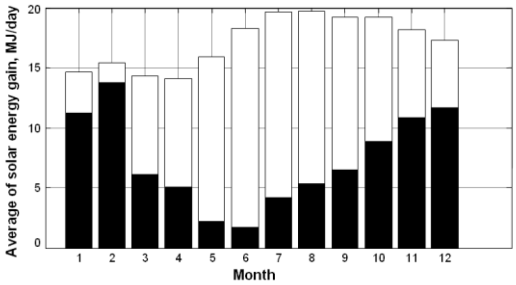

Figure 2. Average solar energy gain (black) bar and the total energy required for the household to heat water (white bar) for month

The variability is evidenced in the results for every thermal solar system parameters of the roofs: orientation, area, slope, relation l/w of the roof. The impact of every parameter was studied and the conclusions are that every house that meet the parameters presents the following average values of design specifications in simultaneous manner: area 35.6 m^2 (roof side);slope of 13.4°; orientation 200-600° (W, N-W) and relation l/w : 1.97. For all this households, the average values of efficiency of the collector, solar fraction, payback period and investment cost are the following: 5.8 %, 48.1 %, 8.8 y and 710.800 Chilean pesos respectively. The total average cost saved in a year is 72,113 Chilean pesos with 80 % of the household with values between 55,900 and 86,300 Chilean pesos. These values represent between 2.3 and 3.6 % of the annual expenditure of the families inside the social-economic group studied which have an average earning of 200,000 Chilean pesos for month. The cost for m^2 of the system was calculated around 20,185 Chilean pesos.

4. Conclusions

The result obtained indicates the theoretical feasibility, technical and economical, to implement a thermal solar systems integrated to the household roofs without a glass protection, promoting an economic and ecological source of energy with the consideration of the fragile economic condition of the region studied and concluding that 56.3 % of the studied households are appropriate to implement the system proposed with an inversion cost of 1million of Chilean pesos with an payback period lower than 10 y and a solar fraction between 30 and 65 %.The performance of the system is highly dependent of the geometry of the household roofs, tilting and spatial orientation, reflected in the large dispersion of the results obtained and, in particular, respect to the values of solar fraction, cost of inversion and payback period. In this sense, it is important to highlight that the process of extraction of the spatial properties of the household is extend. However it is possible to improve it using new technologies like LIDAR. The real application in large scale of this thermal solar system integrated to the household roof without glass protection and its incorporation to the construction practices in Chile require the theoretical knowledge of the potential of incident solar energy and the performance this systems at large scale. This work is a contribution to the theoretical information about the feasibility of implementation of these kind of systems and at the same time represents a model of the enormous potential of the application of the new computational tools applied to 3D modeling and numerical simulation.

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