ENERGETIC, ECONOMICAL AND GEOGRAPHICAL EVALUATION OF DIFFERENT SOLAR THERMALLY DRIVEN HEAT PUMP SYSTEMS FOR HEATING AND COOLING AROUND EUROPE

Juan Rodríguez Santiago [1], Luis A. Bujedo [2]

[1] Fraunhofer Institute for Building Physics, Gottschalkestrasse28a, Kassel, Germany

[2] CARTIF, Parque Tecnológico de Boecillo, 47151 Boecillo, Spain.

1. Abstract

The present work shows an approximation method for solar designers to evaluate the feasibility of solar thermal plants in Europe depending on the type of solar collector used, the coordinates where the system is going to be installed and the types of summer and winter demands to be covered classified by the design temperatures needed for the processes.

This method evaluates the maximum amount of energy able to be captured from the sun to satisfy the needs of a residential building in terms of Domestic Hot Water (DHW), heating and cooling demands.

The final result of the work is a matrix where it is evaluated the combination among:

- Two different technologies of collectors: Flat Plate and evacuated tube collectors
- Two different ways of covering heating demands. Thermal collectors combined with thermal back up and thermal collectors combined with Thermally Driven Heat Pumps(TDHP).
- Energetic and economical results plotted in maps will permit easy comparisons among the configurations.

2. Methodology

The climatic conditions of 513 European locations have been studied to evaluate the relations between the solar thermal renewable energy produced with different combinations of collectors and heat pumps, and the energy demands that a determinate building has in the heating and cooling season. In order to have a representative distribution of the climate around Europe a previous study on the results obtained from the weather stations have been done, eliminating those places sited closer than 50 kilometres to another station and with similar values of Total Horizontal Radiation, Heating Degree Days (HDD) and Cooling Degree Days (CDD).

Once that the division of the European Climates is done, the study of the demands of a determinate domestic building will be done, placing it in all the locations, to obtain dairy the heating, cooling and Domestic Hot Water (DHW) demands, and those diary results will be compared with the diary energy able to be harvested from the sun with the use of different solar thermal technologies. These results will be evaluated in an energetic and economic base to advise on the approximated results that can be obtained from this kind of facilities depending on the configuration and location where they will be installed.

It has also developed the design of a housing type on which to estimate the impact that different European climatic zones can have on it and its associated demand.

3. Study of the European Climates

The resulting 386 locations have been ordered in base to the results obtained for Winter and Summer Climatic Severity parameters (WCS & SCS), based on the Average Global Irradiation and the Winter/Summer degree days of three winter and summer months respectively, as (Duffie &Beckman 1973, ISO13380, CTE) explained, creating a bi-dimensional matrix where all locations are included.

$$WCS = -8.35*10^{-3}*G_{W\,\text{int}} + 3.72*10^{-3}*WDD - 8.62*10^{-6}*G_{W\,\text{int}}*WDD + 4.88*10^{-5}*G_{W\,\text{int}}^{2} + 6.81*10^{-2}$$

(eq. 1)

$$SCS = 3.724*10^{-3}*G_{Summ} + 1.409*10^{-2}*SDD - 1.869*10^{-5}*G_{Summ}*SDD - 2.053*10^{-6}*G_{Summ}^{2} - 5.434*10^{-1}$$

(eq. 2)

Where:

$G_{Wint=}$ Global Average Irradiance cumulated in December, January and February. [kWh/m^2]

$G_{Summ=}$ Global Average Irradiance cumulated in June, July, August and September. [kWh/m^2]

WDD: Average Degree Days (base 20 □C) for December, January and February

SDD: Average Degree Days (base 20 □C) for June, July, August and September.

The results obtained from both climatic severities are lately scaled to comprised in a 0-10 interval, being extreme summer weather values close to 0 for the SCS's and extreme winters those values close to 10 in the case of WCS's.

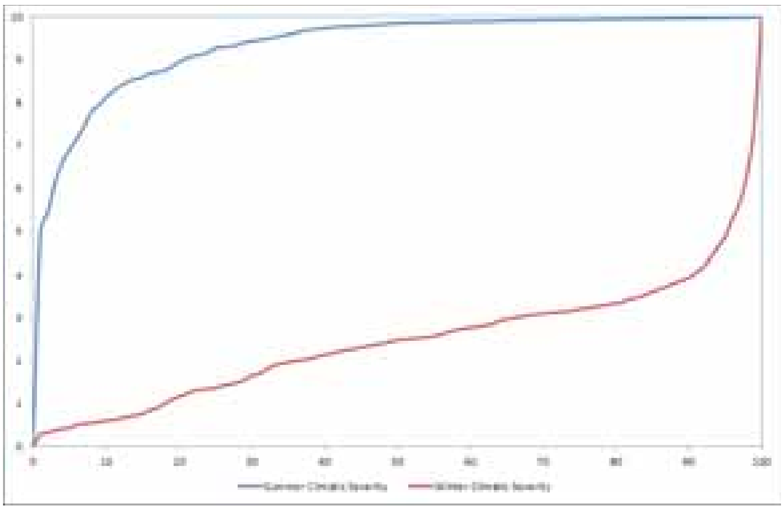

Figure 1: Climatic Severities accumulative distribution for the climate files object of study

This definition of the climatic zones will permit to refer the results obtained for the locations to a finite number of reference places (one by zone), that will be further deeply studied, decreasing the working load of treating data of nearly 400 localities.

In Figure 1, it is shown that the correspondent WCS and SCS values are not homogenously distributed in-between the group:

- Summer Climatic Severities take values over 9 for the majority of the studied cases, appreciating that only a few locations have values under 5. These values show how homogeneous are the summers for most of the European climates. Only a 2% of the values correspond with extremely hot and sunny places. (Figure 2)

- Winter Climatic Severities has a uniform distribution along Europe, with the exception of some Northern climates that nearly duplicate the severity of the rest. (Approximately a 2.5% of the climate locations have extreme winters). (Figure 3)

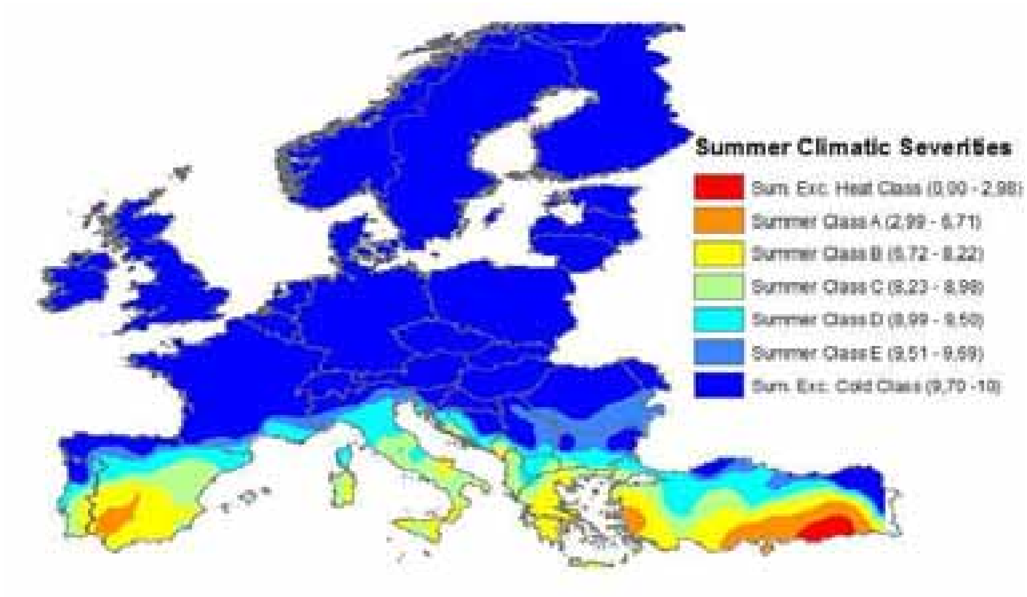

Figure 2: Summer Climatic Severities Spatial Distribution

Figure 3:Winter Climatic Severities Spatial Distribution

This lack of homogeneity produces an irregular distribution of the locations if their WCS and SCS would be treated in quartiles or homogenous linear intervals. In order to solve this problem, the climatic zones are defined by a square 7x7 matrix where the SCS's are represented as columns and WCS's are files. There have been defined for each one of the severity indexes 7 classes, where the first and the last one are those climates previously commented that represent distribution extremes, and the internally five intervals are classified by five equal percentiles of the resting climates. (SCS's lower interval has not been defined due to the uniformity of the data obtained, changing the form of the climatic distribution to a 6x7 matrix). As it can be appreciated , the adopted configuration distribute in an uniform way the climatic files into the classes. (Figure 4).

		Summer Climatic Severities's						
		Exc. Heat	Class A	Class B	Class C	Class D	Class E	Exc. Cold
Winter Climatic Severities's	Exc. Heat	0	0	0	0	0	0	0
	Class 1	3	28	20	13	6	2	0
	Class 2	0	11	12	13	11	4	18
	Class 3	0	0	5	10	9	11	40
	Class 4	0	0	0	2	10	10	34
	Class 5	0	0	0	0	2	8	47
	Exc. Cold	0	0	0	0	1	4	3

Figure 4: Distribution of the 387 weather files into climatic zones.

A combination of the Figure 2 and Figure 3 present a graphical description of the matricidal representation labeled "Figure 4". In this Figure 5, it is easily identifiable those extreme summer and winter climates against the moderated ones.

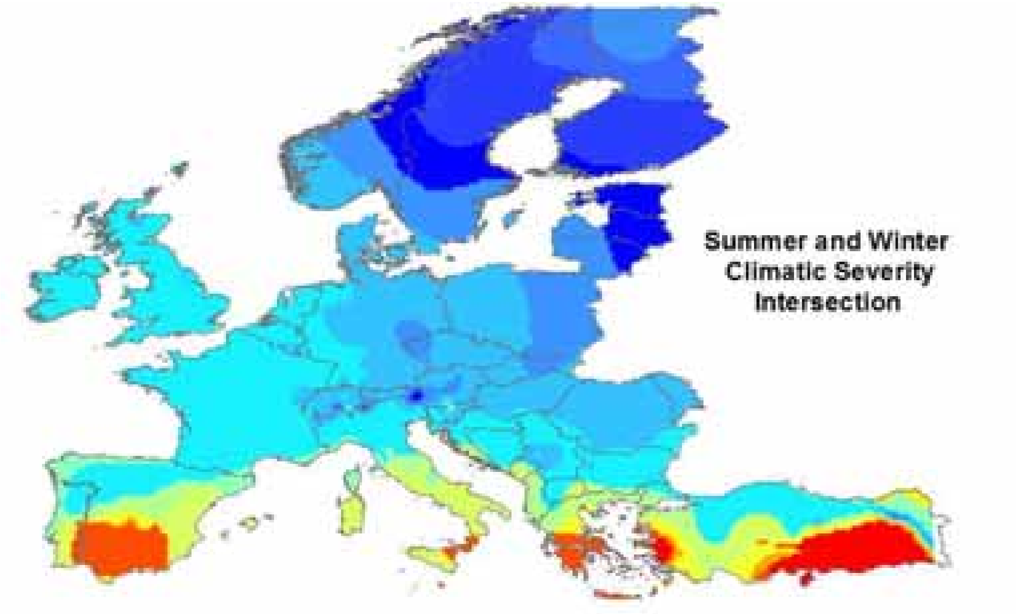

Figure 5: European climatic distribution based on SCS's and WCS's

4. Description of the building

The effect of climatic conditions on domestic buildings has been evaluated with the definition of a building simulated with an hourly code that transform environmental characteristics and internal loads into heating and cooling to be satisfied by the heating and refrigeration facilities. The building simulated for the 387 locations around Europe is a single family house with a compressive area of 100 square meters and 2.4 m height. In order to have all the possible boundaries due to orientations and external conditions, the building is a regular poligon with its eight external walls oriented to the cardinal and intercardinal directions. It hasn't be considered any shadow on the walls, there is an energetic exchange with the surronding ground and the roof interchanges energy with the ambient. This case define the most exposed domestic building typology to the ambient conditions of the places, due to the high ratio external surface/climated space.

The occupancy load is a function of a four people domestic profile and the DHW demand is calculated following (Ulrike Jordan, Klaus Vajen)

Table 1: Main Physical parameters of the simulated building

Average U value (External walls)	0.5	W/m^2K
Average U value (Windows)	1	W/m^2K
Average U value (Ground floor)	0.45	W/m^2K
Average U value (Roofs)	0.35	W/m^2K
Fraction Windows /External Walls	20	%
Fraction Windows /Roofs	0	%
Windows gs value	65	%
Summer Set Point	25	ºC
Winter Set Point	21	ºC

The coefficients that define U values of the external surfaces, give enough insulation for most of the climate classifications of this work, although the authors clearly agree that, in extreme cold cases should be recommendable to have more externally isolated spaces. Analogously, in extreme hot zones, shadowing systems should be planned to avoid excess of solar contributions through the windows. Nevertheless, the building overpass the requirements of most of the European Building codes, letting it be the necessary common object of study for this work.

5. Description of the installed systems

The effect of the climatology on the solar production technologies has been evaluated with two different solar thermal configurations, both of them tested with a flat panel collector and an evacuated tube collector.

Table 2: Characteristics of the thermal collectors

Type of collector	k_0	$k_1[W/m^2K]$	$k_2[W/m^2K^2]$
Flat Plate Collector	0.823	3.02	0.0112
Evacuated Tube Collector	0.601	0.767	0.0062

- The first one harvest all the radiation arriving to the collectors, to drive the domestic hot water demands and the heating demands of the building, distributing the energy in the house through a radiant floor system that works at 35ºC as maximum delivering temperature. The set point temperature of the storage tank is determined by the existence or not of a building heating demand at lower temperatures than the ones needed for DHW. This strategy optimizes the efficiency of the collectors and increase the working periods of the solar facility. When no heating demand exists, the set point temperature of the tank increases to the 60 degrees needed to deliver DHW.
  A back up boiler is installed in serial with the solar plant, to assure the minimum temperatures that the building occupants demand.

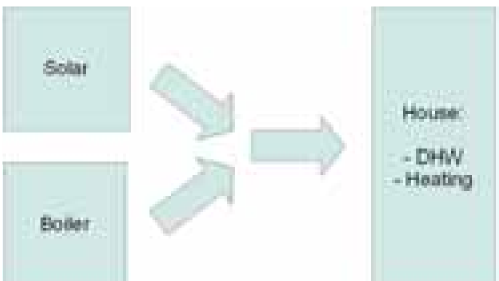

Figure 6: Squema of the first configuration.

- The second case connects the solar plant to a Thermally Driven Heat Pump driven by the collectors and a gas boiler. Solar collectors deliver energy to the evaporator of the heat pump with temperatures around 15 to 20ºC, increasing much more the usage time and the efficiency of the solar facility. The gas boiler drives the heat pump at the optimum working temperature that permits a maximum COP obtaining in the condenser of the machine a temperature of 35 ºC. This condenser is connected to a distribution water tank that delivers the energy to the house. As far as the distribution tank increases the temperature over 35ºC, heating and DHW demand are lower than the heat pump production, this one is stopped and the new set point of the solar plant is moved to 35 in order to work without a gas consume. As happened in the first case, when there is no solar resources available, the gas boiler is connected in serial with the delivering water tank to provide the exact temperatures needed.

In summer time, the solar collectors will be connected directly to the generator of the TDHP to drive it as a chiller, providing the energy needed to cover the cooling load of the building. In this cooling season, the priority is given to the DHW demand, according to the strategy of increasing the efficiency of the solar plant, and the boiler will work as a high temperature back up for the chiller and the DHW systems.

Figure 7: Squemas of the second configurations. (Winter&Summer modes)

In order to compare both solar plants, the number of collectors installed is decided, for each location and collector technology, evaluating the heating and cooling demand of the building in that place and the efficiency of the collectors when the maximum heating and cooling loads occur, dimensioning the solar plant to cover the smaller of both demands. In this way, the system will not be overheated along the year (Along the year, the solar energy harvested will not be higher than the demand of the building) and the total efficiency, as well as the economic results of the system will be optimized.

Table 3: Solar system parameters

Efficiency of the boiler	95 %
Gas Price	0.1 €/ kWh
Electric Price	0.15 €/ kWh
Cooling system Price	900 €/ kW_{Cold}
Flat Plate collector facility Price	700 €/ m^2
Evacuated Tube collector facility Price	1000 €/ m^2

6. Obtained Results

The number of square meters installed to cover the building demands and the return of investment periods for the different solar thermal facilities are going to be shown in the following matrixes and maps. As it can be seen in the Figure 8 and Figure 9, there is an important area that needs more than 40 square meters installed to cover the building demands. The numerical values obtained are printed in the Table 4, divided in the groups determined by the climatic zones previously defined.

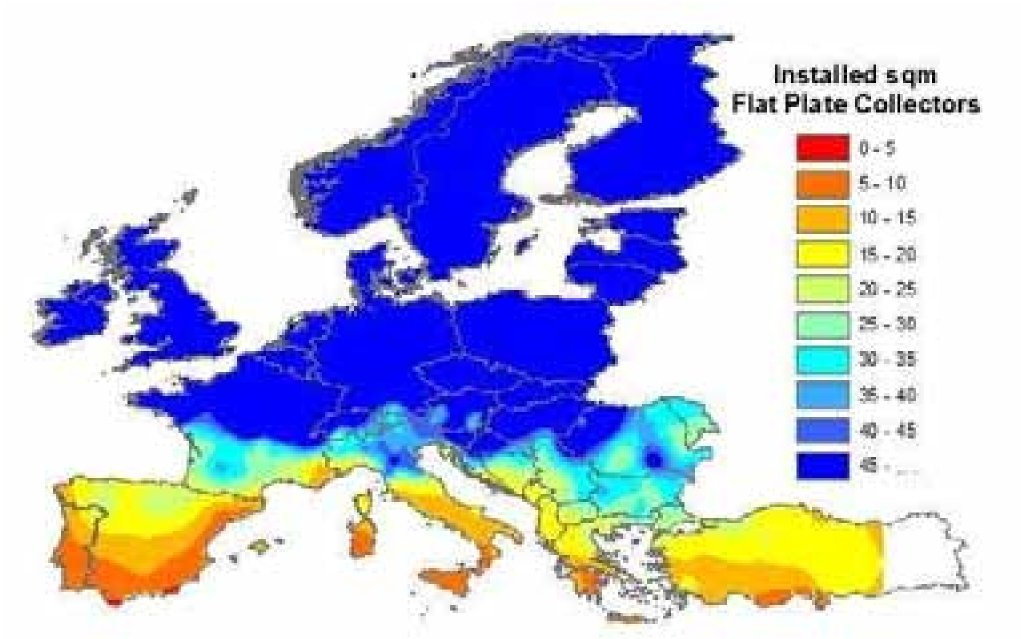

Figure 8 : Flat Plate Collectors that optimize the solar energy contribution [m^2]

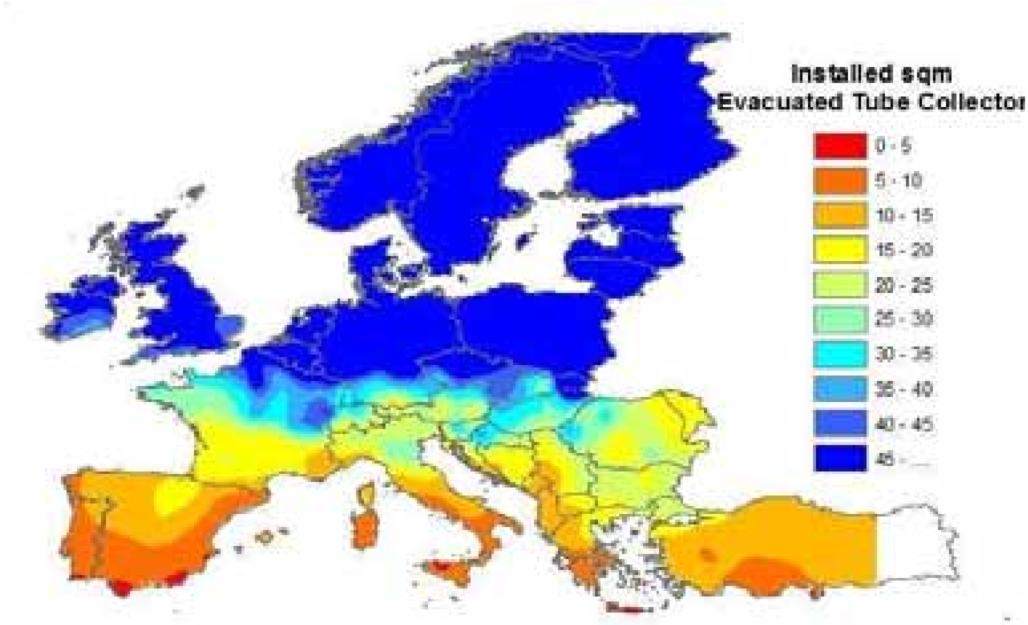

Figure 9: Evacuated Tube collector that optimize the solar energy contribution [m^2]

Table 4: Number of square meters for each climatic zone (FP &ET)

Flat Plate [sqm]		Summer Climatic Severities's						
		Exc. Heat	Class A	Class B	Class C	Class D	Class E	Exc. Cold
Winter Climatic Severities's	Exc. Heat	—	—	—	—	—	—	—
	Class 1	*8,39*	8,38	9,39	16,93	14,55	11,47	*18,88*
	Class 2	*16,62*	18,83	24,12	24,90	47,87	53,15	*56,95*
	Class 3	—	—	25,86	32,46	80,42	95,12	*88,11*
	Class 4	—	—	—	33,32	99,66	74,30	*92,34*
	Class 5	—	—	—	19,01	—	—	—
	Exc. Cold	—	—	—	—	—	—	—

Evacuated Tubes [sqm]		Summer Climatic Severities's						
		Exc. Heat	Class A	Class B	Class C	Class D	Class E	Exc. Cold
Winter Climatic Severities's	Exc. Heat	—	—	—	—	—	—	—
	Class 1	*6,73*	6,63	7,41	12,01	11,14	8,75	*11,78*
	Class 2	*15,82*	14,85	17,69	17,80	25,75	28,28	*29,25*
	Class 3	—	—	16,94	20,81	38,57	49,25	*38,29*
	Class 4	—	—	—	21,41	40,29	35,86	*42,93*
	Class 5	—	—	—	12,53	—	—	*58,72*
	Exc. Cold	—	—	—	—	—	—	—

Figure 10 and Figure 11 represent graphically the number of years needed to recover the invesment of each one of the thermal facilities installed to deliver hot water for heating and DHW purposes. Table 5 represent the numerical results sorted by climatic zones.

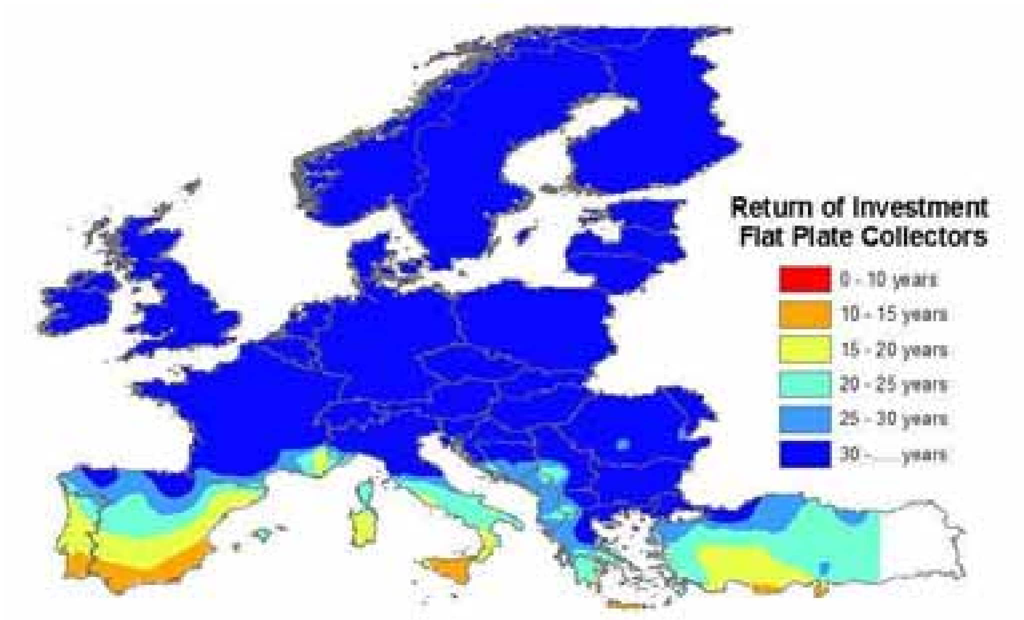

Figure 10: Return of investment. Flat plate collectors. (DHW & Heating demands) [years]

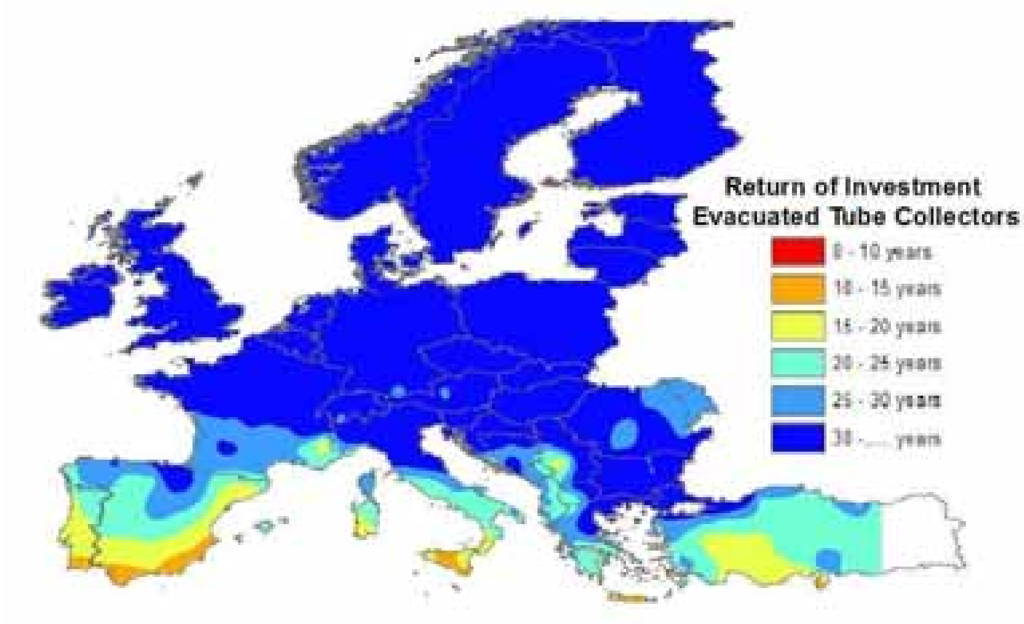

Figure 11:Return of investment. Evacuated tube collectors. (DHW & Heating demands) [years]

Table 5: Return of Investment for both solar thermal technologies

Return of Investment Flat Plate [yr]		Summer Climatic Severities's						
		Exc. Heat	Class A	Class B	Class C	Class D	Class E	Exc. Cold
Winter Climatic Severities's	Exc. Heat	—	—	—	—	—	—	—
	Class 1	*18,84*	16,28	17,65	28,42	25,78	21,02	*30,24*
	Class 2	*24,25*	29,09	34,89	36,38	59,53	65,68	*63,30*
	Class 3	—	—	35,51	43,29	93,98	117,55	*85,30*
	Class 4	—	—	—	39,81	95,60	82,02	*98,14*
	Class 5	—	—	—	22,52	—	—	—
	Exc. Cold	—	—	—	—	—	—	—

Return of Investment Vacuum tubes [yr]		Summer Climatic Severities's						
		Exc. Heat	Class A	Class B	Class C	Class D	Class E	Exc. Cold
Winter Climatic Severities's	Exc. Heat	—	—	—	—	—	—	—
	Class 1	*18,38*	17,65	19,00	27,05	26,22	21,87	*29,05*
	Class 2	*26,62*	30,13	34,12	34,71	43,11	47,10	*44,82*
	Class 3	—	—	31,24	36,87	60,27	71,43	*55,91*
	Class 4	—	—	—	34,15	54,72	54,52	*61,33*
	Class 5	—	—	—	20,30	—	—	*71,02*
	Exc. Cold	—	—	—	—	—	—	—

When the solar thermal plants defined in Table 4 are used in combination with a sorption machine for summer and winter uses, the results obtained are represented graphically in the Figure 12 and Figure 13. The numerical results are shown in Table 6.

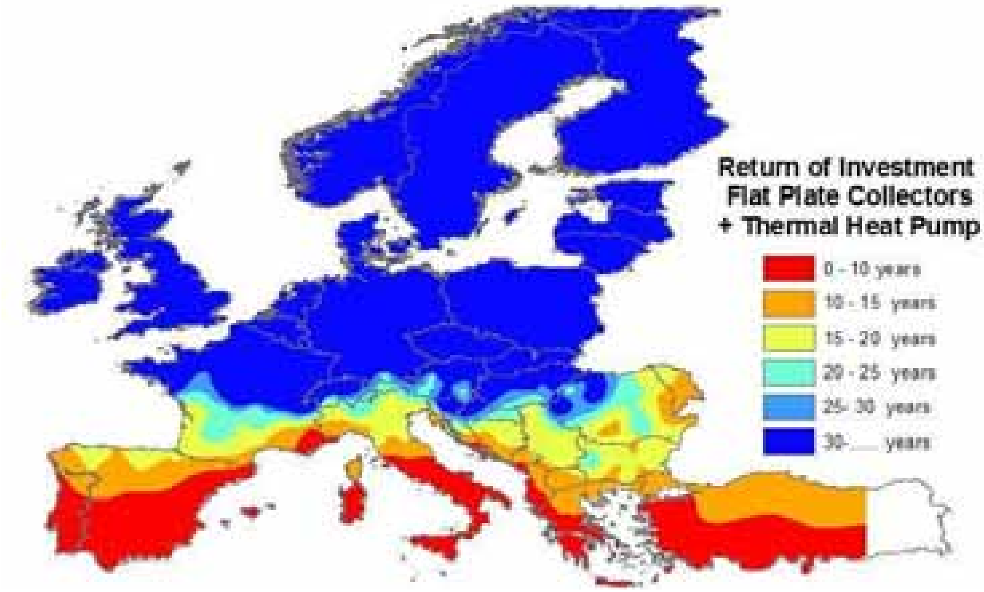

Figure 12: Return of investment for a TDHP combined with Flat Plate Collectors [yr]

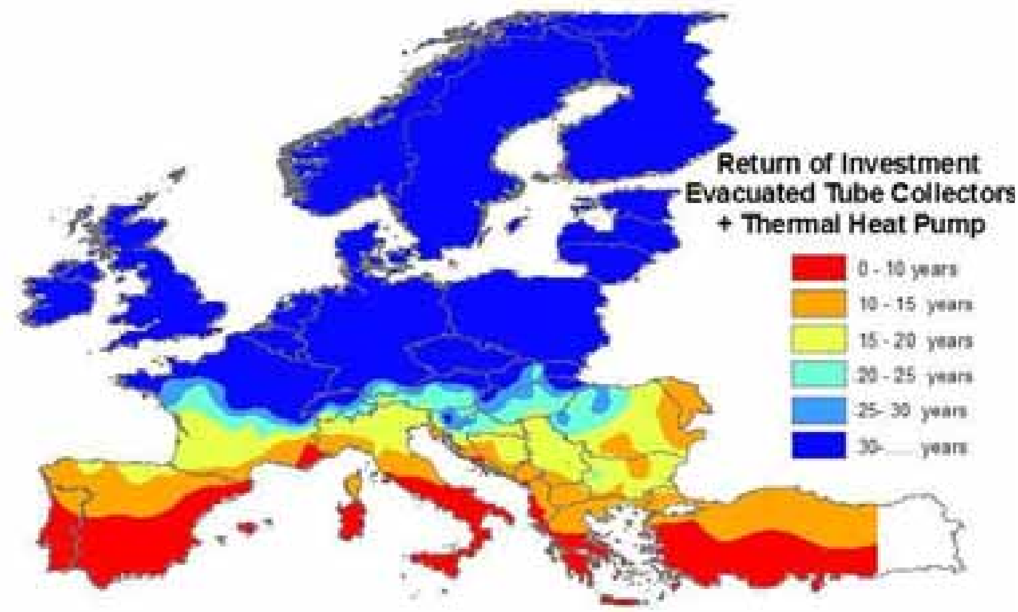

Figure 13: Return of investment for a TDHP combined with Evacuated Tube Collectors [yr]

Table 6: Return of Investment for both solar thermal technologies combined with thermal Heat pump

Return of Investment Flat Plate + HP [yr]		Summer Climatic Severities's						
		Exc. Heat	Class A	Class B	Class C	Class D	Class E	Exc. Cold
Winter Climatic Severities's	Exc. Heat	—	—	—	—	—	—	—
	Class 1	*6,04*	6,82	7,53	11,01	11,26	10,20	*13,95*
	Class 2	*7,10*	9,47	12,20	13,79	40,47	49,18	*44,22*
	Class 3	—	—	12,53	15,76	67,19	94,54	*58,18*
	Class 4	—	—	—	16,22	68,54	48,99	*64,88*
	Class 5	—	—	—	12,28	—	—	—
	Exc. Cold	—	—	—	—	—	—	—

Return of Investment Vacuum tubes +HP [yr]		Summer Climatic Severities's						
		Exc. Heat	Class A	Class B	Class C	Class D	Class E	Exc. Cold
Winter Climatic Severities's	Exc. Heat	—	—	—	—	—	—	—
	Class 1	*6,58*	7,37	8,06	11,05	11,28	10,81	*13,04*
	Class 2	*7,99*	10,23	12,46	13,84	30,51	37,21	*22,36*
	Class 3	—	—	12,05	14,69	43,87	61,37	*20,33*
	Class 4	—	—	—	14,99	39,42	33,66	*43,63*
	Class 5	—	—	—	12,14	—	—	*32,83*
	Exc. Cold	—	—	—	—	—	—	—

7. Conclusions

The study developed in this article demonstrates the efficiency of the combination between solar thermal technologies and thermally driven heat pumps around Europe for a determinate building and occupancy profile. The prices studied are averages of the gas prices published in (ESTIF) although nowadays the cost of each kWh gas in Europe is higher and as a consequence the periods of investment of the studied systems are shorter.

The boundary condition imposed to avoid energetic overproduction when there are no heating, cooling or DHW demands present a lower amount of Evacuated Tube collectors installed in comparison with the Flat Plate ones. This smaller solar plant is not always translated to the user as a cheaper facility due to the elevated price of the tubes and the climate severity of some European zones. Locations placed in southern Europe with severe summers in terms of high radiation and elevated temperatures, and soft winters have better economical results when installing Flat Plate collectors to provide thermal energy in winter use or also when a thermal heat pump is installed, to deliver cold water in summer. In the rest of the European zones, fit better the combination of the building with Evacuated Tube collectors.

When the return of investment is the parameter chosen to decide the facility, it must be explained that only a limited amount of climatic zones have acceptable results (less than 20 years) when the solar plant is only installed to deliver energy for heating and domestic hot water, but the numbers decrease drastically when a combination with a sorption machine able to work in cooling and heating mode is done.

In every climate condition defined by low Winter Severity indexes or Summer Severity indexes below the class C, the combination of solar collectors with thermally driven heat pumps are acceptable options in terms of energetic and economical savings.

8. References

ASHRAE Handbook 1997. Fundamentals References

Duffie J.A., Beckman W.A. SOLAR ENGINEERING OF THERMAL PROCESSES. 1st Ed. Wiley&Sons

Henning, H.M, Solar Assisted Air Conditioning in Buildings – A Handbook for planners, 2003

Rodriguez, J., Fedrizzi, R. Description and Visual Representation of Most Promising Markets. SolarCombi+, Deliverable EU Project,

ESTIF, “Solar Thermal Markets in Europe, Trends and Market Statistics 2008”, Bruxelles, May 2009.

CTE. Codigo tecnico de la edificación. DB-HE Ahorro de Energía. Apendice D.

ISO 13370:2007:Thermal performance of buildings -- Heat transfer via the ground -- Calculation methods

Ulrike Jordan, Klaus Vajen. Realistic Domestic Hot-Water Profiles in Different Time Scales. IEA Task26