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Defining an annual energy output ratio between PV and solar thermal

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Abstract

Photovoltaics (PV) and solar thermal (ST) collectors are often competing between themselves not only because the investment capacity is limited but also because the energy demand and roof space is limited and both types of panel provide energy which can be converted to a different type of energy under a certain efficiency. Therefore, it makes sense to develop a ratio that quantifies the difference in annual energy output between standard ST and PV for different locations. This ratio is useful, for example, to support the decision between installing ST or PV, when combined with other local specific information such as the value of heat and electricity for a specific location and application, the system complexity and efficiency, and others.

A market survey was conducted for assessing the average performance specifications of the panels. Simulations were conducted and several ratios were plotted in the world map. Despite the large variations occurring due to local climate, the ratio increases at lower latitudes due to two factors: a) the efficiency of a PV panel is reduced with the increase of air temperature while, in solar thermal, the effect is the opposite; b) Under low intensity solar irradiance, the efficiency of a PV panel is maintained while a solar thermal collector can have its efficiency reduced to zero. For latitudes lower than 66º, the ratio flat plate at 50ºC to PV is ranging from 1,85 to 4,46 while in the ration between vacuum tube at 50ºC and PV from 3,05 to 4,76.

Keywords: PV, Solar Thermal, Annual energy output ratio, Market survey, World map, Climate

1. Introduction

1.1. The effect of solar radiation in the power and efficiency of PV and solar thermal collectors

Fig. 1 shows the effect of solar radiation on both power and efficiency for photovoltaics (PV) panels and solar thermal (ST) collectors which is calculated according to a simplified model using the following simplified formulas:

Photovoltaic panels: $P = I \cdot \eta$ (eq. 1)

Solar thermal collectors: $P = \eta_0 \cdot I - U \cdot \Delta T$ (eq. 2)

In equation 2, the heat loss value (U) is already including both components U1 and U2. Figure 1 show a graphical representation of the above formulae.

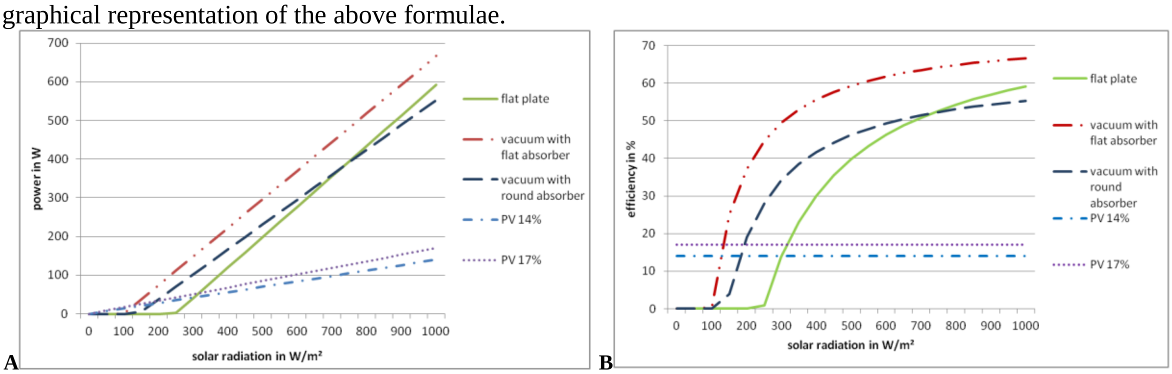

Fig. 1 The impact of solar radiation on power (A) and efficiency (B) for both PV and T collectors at a ΔT of 50°C

The collector values used to plot the above graphs were taken from a market survey conducted by this team that is shown below. These values represent standard thermal collector and refer to the aperture area of collectors working under a ΔT = (Tmed – Tambient) = 50°C. In this model, only the most relevant factors are taken in consideration. In reality, there are other factors to consider, such as the fact that the temperature of the solar cells will increase together with the solar radiation, which will lead to a decrease in solar cell efficiency. This means that the efficiency of the PV collector is not a straight line as shown but decreases with solar radiation following a coefficient of around 0,44%/ºK for mono crystalline solar cells (Wagner et al, 2010). In the same manner, the PV power curve will continue to increase with solar radiation but the real curve is less steep than that shown above. However, the efficiency of solar cells is also increased for higher solar radiations which somewhat compensates for this effect (Green, 1981).

Fig. 1 shows that the efficiency of a PV-system is almost independent of the solar irradiance, while on solar thermal-systems the efficiency is strongly dependent. The efficiency of a thermal collector is often zero at low solar radiation intensities.

1.2. The effect of temperature in the efficiency of PV and T collectors

Figure 2 shows the effect of operating temperature on the efficiency of the solar panels and was calculated using the formulae 1 and 2. For the PV panels, the cell temperature dependency was taken into account as described above.

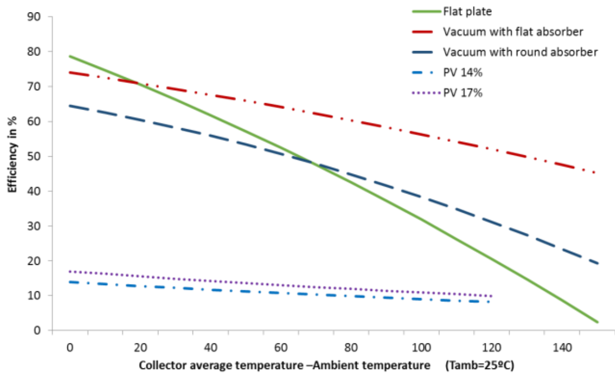

Fig. 2 The impact of temperature in efficiency on PV and ST panels at a constant solar radiation of 1000W/m^2

The operational temperature of a PV panel varies according to how much solar radiation is received and how much heat the panel is able to lose, which is greatly influenced by factors like panel construction or type of installation (building integrated vs free standing). The operating temperature of a PV panel is defined by the nominal operating cell temperature (NOCT). For this graph, it was accepted that 120º Celcius was the maximum temperature for the PV panel since many panels break after that temperature (Wenham et al, 2007).

The operational temperature of a ST collector is affected by the same 2 factors has the PV panel plus the heat that is being carried away from the collector by the fluid that is running inside the ST collector. This fluid can be water, glycol or a special type of oil. The amount of heat that is carried away by the fluid temperatures depends on factors like the temperature difference between the fluid and the collector, the ambient temperature, the characteristics of the fluid and the speed and type of flow (Duffie et al, 1974).

A major difference between PV and ST panels is that, in ST panels, it is possible to control the average temperature of the panel while in PV panel this temperature is not controlled. The similarity between both types of panels is the efficiency goes up when the operating temperature is decrease.

1.3. Influencing factors: local climate

Weather conditions vary immensely around the globe. As an example, figure 3 shows the variation on beam radiation around the world while figure 4 shows the annual average temperature. Many other parameters, such as the median daily variation of temperature or the humidity in the air could be shown to illustrate these large variations.

The numbers in figure 3 show the percentage of beam radiation in the total solar radiation that hits the ground while the color shows the total amount of solar radiation. As recognizable on the above map, the beam fraction is not dependent of the latitude although the total amount of solar radiation increases at lower latitudes. The main influence on the beam fraction is the local climate (Chen et al, 2011).

The percentage of beam radiation in the total radiation ranges from 43% in Singapore to 77% in El Paso and Tamanrasset. Singapore, Naha, Chon Buri, Manaus and Bergen are the only five cities on the map in which the diffuse radiation represents more than 50% of the annual solar radiation received in the ground. The main reason for this effect is the presence of clouds (Benestad, 2002). Around the globe, the variation in climate is very large. The cities in Southeast Asia are affected by the monsoon, which is twice every year. The climate there is moist tropical. Bergen has around 200 rainy days over the year and a moderate climate (ClimaOnline, 2014). Manaus is located close to the equator and is affected by a long rainy season, which leads to the 48% of beam in the total solar radiation. Whereas in desert areas like El Paso or Tamanrasset, the climate is dry and the ratio reaches up to 77%.

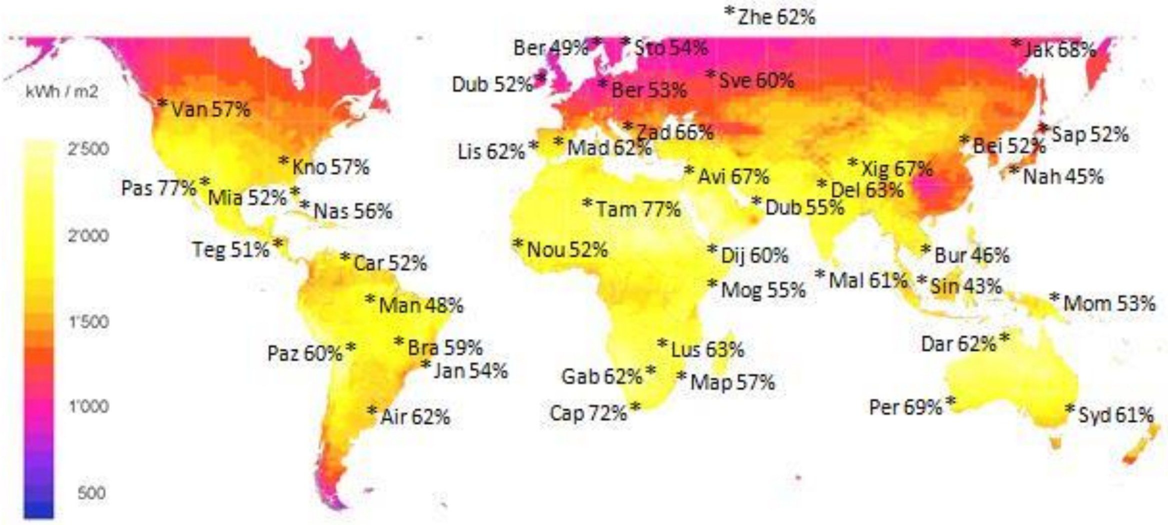

Fig. 3: Percentage of beam in the total solar radiation (number) and total solar radiation in different locations (color)

As expected, the countries closer to the equator show the warmest average temperature around the world which go up to 30°C. However, there are exceptions like La Paz with 8,2ºC. The low annual temperature of La Paz is probably due to the high altitude. At high altitudes, the layer of atmosphere is less dense which leads to both higher temperature variations (the atmosphere has less capacity of retaining the heat) and higher solar radiation (the atmosphere is less dense and absorbs less solar radiation). The main cause of low temperatures at higher latitudes is the angle at which the incoming rays hit the ground. Although, the solar radiation in a perfect sunny day is close to 1000W/m^2 anywhere in the world, if the sunlight has a lower angle, that sunlight will be spread over a larger area. This effect is also known as the cosine effect. (Benestad, 2002).

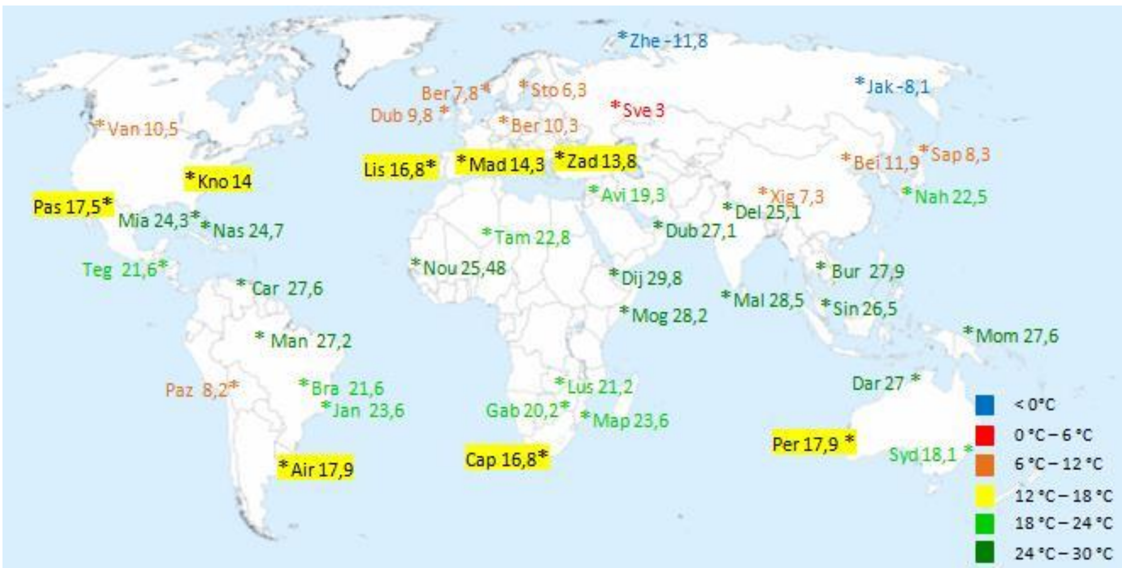

Fig. 4: Annual average temperature of 66 cities around the globle

Locations with the same annual temperature may present very different temperature profiles. For example, comparing Lisbon and El Paso that have similar annual temperatures around 17ºC, it can be found that the temperature is very steady in Lisbon, a coastal city with a Subtropical-Mediterranean climate while El Paso has very large variations over 24hours and a hot desert climate. Another example is the climate on the West Coast of Europe is much milder than the climate in the interior of Europe. This is due to the effect of the Gulf Stream that not only warms up the air but also stabilizes its temperature (Aguado et al, 2012).

1.4. Defining an annual energy output ratio between PV and solar thermal

PV and ST collectors are often competing between themselves not only because the investment capacity is limited but also because the energy demand is limited and both types of panel provide energy which can be converted to a different type of energy under a certain efficiency. Additionally, roof area can sometimes be a restriction to the installation of further solar panels.

Moreover, the climate variations described in the previous chapter lead to large differences in the performance of solar panels around the globe. Additionally, each type of solar collector has a different response to these variations.

Therefore, it makes sense to develop a ratio that quantifies the difference in annual energy output between standard solar thermal collectors and PV panels for different locations. This ratio is useful, for example, to support the decision between installing ST or PV, when combined with other local specific information such as the value of heat and electricity for a specific location and application, the system complexity and efficiency, and even the local installers knowledge or the available offer. This ratio was defined as following:

$$Ratio\ Between\ \mathrm{ST}\ and\ PV = \frac{Annual\ Energy\ Output\ per\ m2\ of\ ST\ collector}{Annual\ Energy\ Output\ per\ m2\ \mathrm{of}\ PV\ panel} \qquad \text{(eq. 3)}$$

The ratio was calculated for the different types of panel types. Two types of PV panels were considered: average monocrystalline and polycrystalline panels. Two types of ST panels were considered: Flat Plate and Vacuum Tube. Additionally, for ST collectors, the following collector average temperatures were investigated: 30ºC, 50ºC and 80ºC.

The ratio was calculated and analyzed for the 3 temperatures but only the middle temperature (50ºC) is shown in world maps with the ratio.

2. Market Survey

A detailed market survey was carried out to discover both the prices and standard collector specifications for both PV and ST collectors in January of 2014. The ST survey included a total of 90 collectors of 3 types: flat plate, vacuum tube with flat absorber, vacuum tube with round absorber. This survey comprised 43 companies in 16 countries. All collectors were tested according to the standard EN 12975 (Institut für Solartechnik, 2014) and an average was made. This average is displayed in table 1.

Table 1: Values for different T collectors

Type of Panel	ABSORBER			APERTURE			GROSS		
	η0 (%)	U1 (W/m²K)	U2 (W/m²K)	η0 (%)	U1 (W/m²K)	U2 (W/m²K)	η0 (%)	U1 (W/m²K)	U2 (W/m²K)
Flat Plate	80,3	3,967	0,009	78,6	3,877	0,008	71,3	3,526	0,008
Vacuum with round absorber	74,1	2,088	0,009	64,4	1,809	0,008	39,9	1,117	0,005
Vacuum with flat absorber	82,0	1,626	0,004	74,0	1,468	0,003	54,9	1,085	0,003

The PV survey looked into 150 different PV panels from 35 companies of 9 countries. A standard average efficiency was found for both polycrystalline and monocrystalline panels and is shown in Table 2.

Table 2: Average efficiency for monocrystalline and polycrystalline modules

Type of PV panel	Efficiency
Monocrystalline	16,5%
Polycrystalline	14,6%

Finding out the price of modules was more complex process and some uncertainty lingered, as the price variations that was found were considerable large. The prices that our market survey found for PV were 15% lower than PVXchange. The ST prices were also found to vary substantially so a similar error margin is incurred. The following tables describe the prices that were found in the market study.

Tab. 3: Price of a ST collector in € per gross and aperture area

Type of ST panel	Flat Plate	Vacuum Tube with Flat absorber	Relative difference between FP to VT
Sale with VAT (consumer) in €/m² gross	158	166	5%
Sale with VAT (consumer) in €/m² aperture	187	275	32%
Relative difference gross to aperture area	15%	40%	-

Tab. 4: PV Price from cell to panel in €/Wp

Type of PV panel	Poly	Mono	Unit
Cell price	0,27	0,31	€/Wp
Panel sale price with VAT (consumer)	0,52	0,56	€/Wp
Price increase from cell to panel	1,91	1,80	-

Tab. 5: Price comparison PV to ST (including VAT) at consumer level in EU (custom cleared)

Type of Solar panel	Price €/m² aperture	Comparison to Poly	Comparison to VT
ST Flat Plate	187	179%	68%
ST Vacuum Tube with flat absorber	275	263%	100%
PV Polycrystalline	104	100%	38%
PV Monocrystalline	127	122%	46%

3. Simulation

Winsun is a TRNSYS based solar simulation software that was developed by Bengt Perers and Björn Karlsson for Lund University. Winsun is able to simulate the annual performance of a collector. The inputs and outputs of the program are described in figure 5.

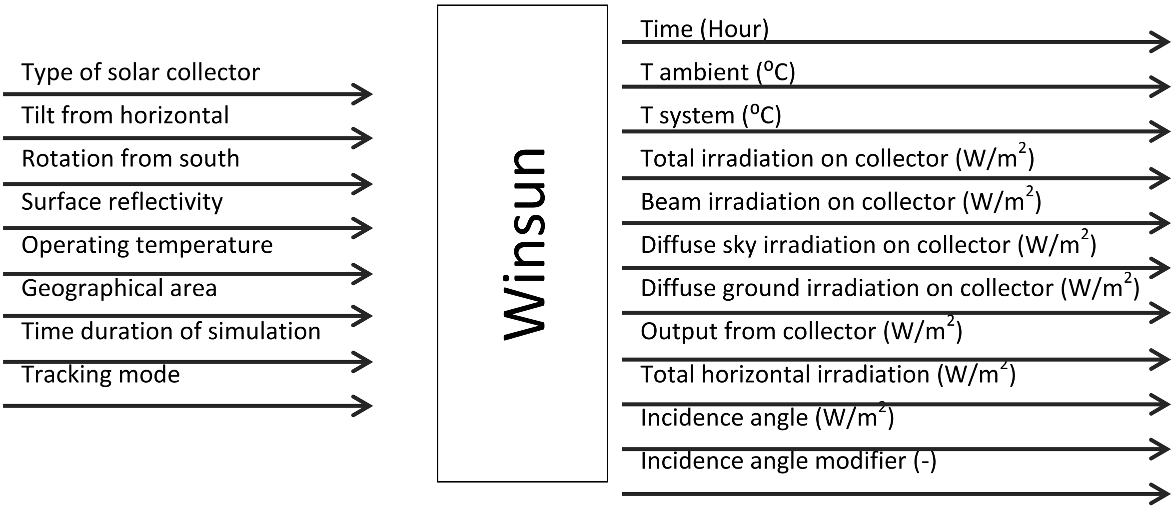

Fig. 5: Winsun's inputs and outputs (source: Brand et al, 2014)

A new collector file was made for Winsun based on the survey findings regarding the standard collector specifications per aperture area. The values for efficiency and heat losses were taken from the table 1. For all performed simulations, the collector was stationary at a tilt equal to the latitude of the selected city.

Simulations were performed for 66 cities around the world in a range of different latitudes and climatic regions in order to obtain a good visualization of the variation of the ratio in the world map.

4. Analysis of Results

Winsun simulated the performance of PV and ST panels over the year and provided the annual output per m^2 of aperture area. For all locations and for a working temperature of 50ºC, the ST panel always produces more energy than PV. As expected, this is also true for a ST operating temperature of 30ºC but at an operating temperature of 80ºC, there is one city in Russia and one city in Norway where the flat plat was performing worse than a PV. Vacuum tube still performed better than PV due to lower heat loss factor. Additionally, around the world, vacuum tubes normally outperform flat plate collector per aperture area for temperatures of 50ºC and 80ºC. But for a temperature of 30ºC, the flat plate is sometimes outperforming the vacuum tube with flat absorber, especially in warm location. This is due to the fact that flat plates have 5%

higher peak efficiency. The main reasons for this is that the standard efficiency of the flat plate that was found in the market survey is 5% higher than for vacuum tube with flat absorber whereas the heat losses of the vacuum tube with flat absorber are much lower. This is further detailed by the following formulas:

$$Q = \eta_{0b} \cdot K_b(\theta) \cdot G_b + \eta_{0b} \cdot K_{diffuse} \cdot G_d - U_1(T_m - T_a) - U_2(T_m - T_a)^2 \quad \text{(eq. 4)}$$

$$K_b(\theta) = 1 - b_0 \cdot \frac{1}{\cos(\theta) - 1} \quad \text{(eq. 5)}$$

The annual energy output ratio between PV and ST was then calculated for the 66 cities. Four world maps were then plotted to show the ratio between ST at 50ºC and PV in 66 cities. All maps show how much more energy the ST produces comparing to the PV. In general, the ratios are increasing when the latitude is decreasing. An example of this ratio is shown below for 3 cities for 3 different latitudes close to the Equator, Tropic of Capricorn and Arctic Circle line.

Table 6: Irradiance (kWh/m^2), panel outputs (kWh/m^2) and ratios for both PV and ST

City and Country	Tilt (º)	Solar Radiation (kwh/m2)		Output (kwh/m^2)				Ratio			
		Total	Beam	PV14,6%	PV16,5%	Flat Plate at 50°C	Vacuum Tube with flat absorber at 50°	Flat Plate 50ºC to PV14,6%	Flat Plate 50ºC to PV16,5%	Vacuum 50ºC to PV14,6%	Vacuum 50ºC to PV16,5%
Nairobi, Kenya	1	1930	1089	259	293	950	1141	3,7	3,2	4,4	3,9
Rio de Janeiro, Brazil	23	1771	953	236	267	893	1054	3,8	3,3	4,5	3,9
Umea, Sweden	64	1273	600	163	185	429	629	2,6	2,3	3,8	3,4

As shown in the above table, the ratio between a flat plate working at 50ºC and a policrystalline PV panels varies considerably. In Nairobi, the flat plate will produce 3.7 times more energy than the PV with 14.6% efficiency while for Rio de Janeiro this ratio is 3.8. These two cities are an example that the ratio does not always increase when moving towards the equator. In Umea, the ratio is considerably lower at 2.6.

Each legend in the map has the same scale for the next four maps. The scale goes from green (stronger ST location) to blue (weaker ST location). The blue color is an extreme case which only happens in very specific situations.

Fig. 6: Ratio Flat plate 50°C to PV 14.6% polycrystalline

Figure 6 shows the ratio between a flat plate collector working at an average temperature of 50°C and a polycrystalline module with an efficiency of 14.6%. The lowest ratio of 1.54 is found in the coldest place with the highest latitude. On the opposite end, the city of Dijbouti at latitude of 12° reaches a ratio of 4.46 signaling the over-performance of ST facing PV.

Singapore is an exception, since it has a considerably lower ratio than the other cities at similar latitudes. This is mostly caused by a long duration of the cloudy rain season (Aguado et al, 2012), which also leads to the lower ratio of beam to total radiation as shown in figure 2. All four maps show that for locations with high diffuse radiation or low ambient temperature, the ratio goes down which means that ST is producing less energy in comparison to the PV.

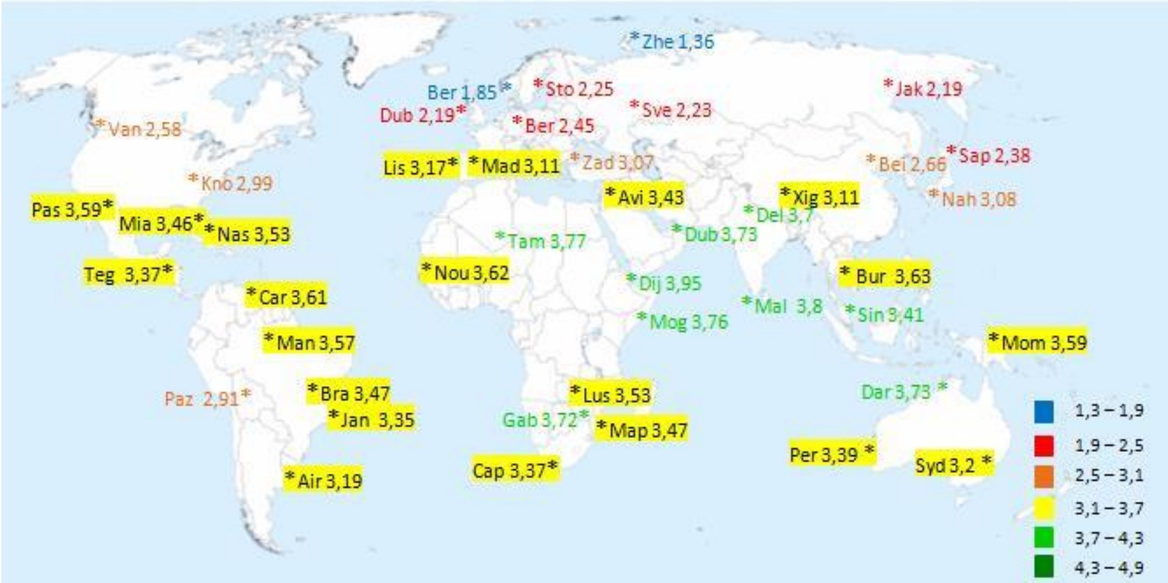

Fig. 7: Ratio Flat plate 50°C to PV 16.4% monocrystalline

Figure 7 shows the annual energy output ratio between flat plate working at 50ºC and monocrystalline PV with 16.4% of efficiency. The ratios in figure 7 are lower than in figure 6, once the monocrystalline modules have a higher efficiency than the polycrystalline. The ratio from ST to mono is always around 88% of the ratio of ST to poly. This happens for both vacuum tubes and flat plates collectors.

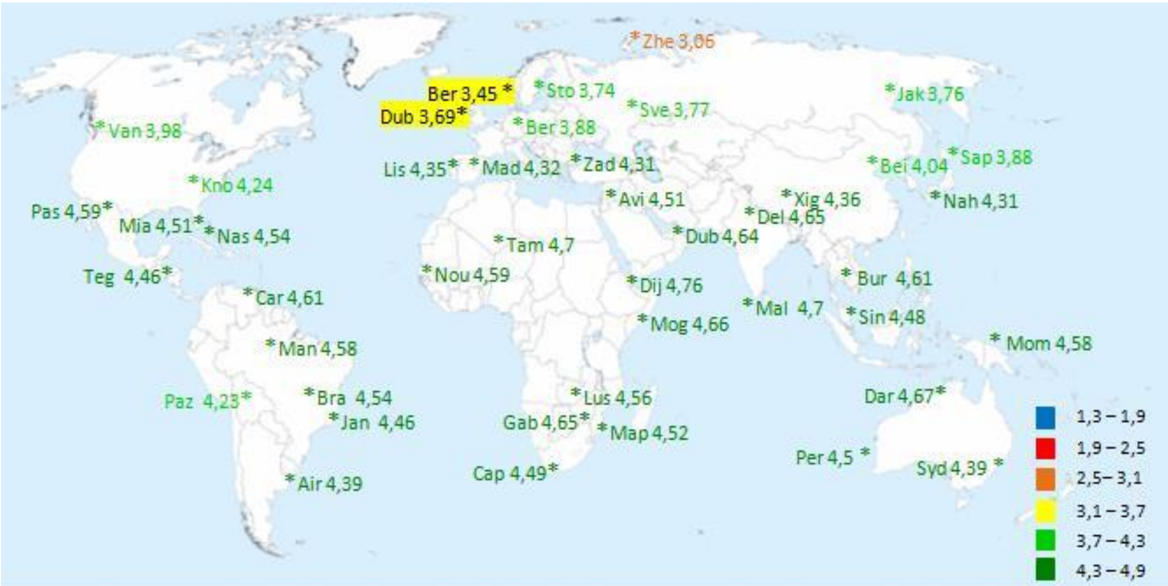

Fig. 8: Ratio Vacuum tube with flat absorber 50°C to PV 14.6% polycrystalline

As expected, the ratio between vacuum tube with flat absorber and the poly modules show the highest values in all four maps. For a ST working temperature of 50ºC, the highest ratio value was found to be 4.76 in Dijbouti, a city located close to the equator with a warm average temperature of 30°C (Aguado et al, 2012).

The lowest ratio in figure 8 is 3.06 which is considerably higher than the lowest ratio found in figure 6 that shows the ratio between flat plate and polycrystalline PV which is 1.36. This can be explained by the extremely low temperatures in this location. In between latitudes of 40ºN and 40ºS, all ratios on the map are above 4.2.

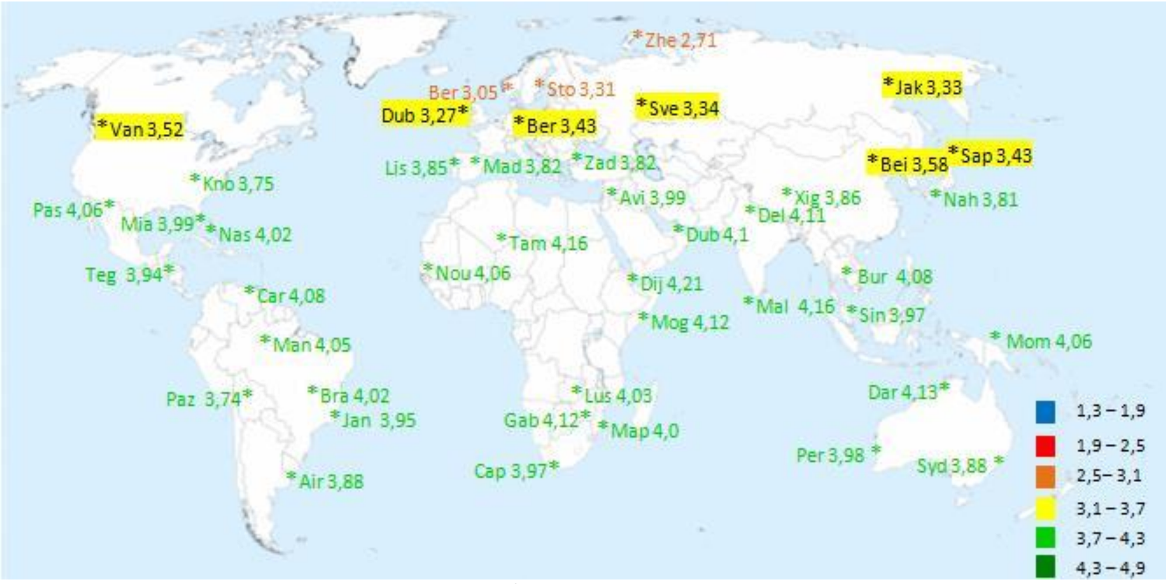

Fig. 9: Ratio Vacuum tube with flat absorber 50°C to PV 16.4% monocrystalline

From the four maps shown in the paper, figure 9 has the smallest variation between the highest and lowest ratio. This variation is 1.5. The highest ratio found was 4.21 which is lower than the highest ratio between flat plate to poly which is 4.46.

In all maps, the lowest ratio is always Cape Zhelaniya (Russia) and the highest ratio of the graph is in Dijbouti.

5. Conclusions

A market survey was conducted that determined the average performance and price values for a few types of ST and PV panels. These performance values were then used to simulate the annual energy output of each type of panel. This was the basis for establishing a qualitative comparison betwen ST and PV panels, the annual energy output ratio. In order to facilitate the interpretation those results, several world maps were drawn that graphically show the differences in annual energy production of the different solar technologies.

On a world scale, this ratio tends to increase at lower latitudes which is clearly visible in figures 6, 7 , 8 and 9. This happens despite large variation being introduced by local climate. The higher ratios at low latitudes mean that ST panels are performing comparatively better than PV and the inverse for higher latitudes. The two main factors responsible for this are:

- The efficiency of a PV panel is reduced with the increase of air temperature while in solar thermal the effect is the opposite.
- Under low intensity solar irradiance, the efficiency of a PV panel is maintained while a solar thermal collector can have its efficiency reduced to zero.

For the annual energy simulations and the ratio maps, the following conclusions could be drawn:

- For all locations and for a working temperature of 50ºC, the ST panel always produces more energy than PV.
- Around the world, vacuum tubes with flat absorber normally outperform flat plate collector per aperture area for temperatures of 50ºC and 80ºC. However, the price per aperture area of vacuum tube with flat absorber is also 32% higher than flat plate. This means that, assuming that the installation cost is the same for both ST technologies, vacuum tubes should be preferred only if the its annual output is higher than flat plate annual output by 32%.
  For a temperature of 30ºC, the flat plate is sometimes outperforming the vacuum tube with flat absorber, mainly in warm location.
- All four maps show that for locations with high diffuse radiation or low ambient temperature, the ratio goes down which means that ST is producing less energy in comparison to the PV.

- For latitudes lower than 66º, the ratio flat plate at 50ºC to PV is ranging from 1,85 to 4,46 while in the ration between vacuum tube at 50ºC and PV from 3,05 to 4,76. These numbers can be an important tool when making the decision of going for PV or ST. However, it is important not to forget that dimensioning ST installations so that all the energy is utilized is key in generating good revenue from projects
- The ratio was also calculated for ST operating temperatures of 30ºC and 80ºC. As expected, the ratio goes up for 30ºC (meaning that it is more favorable to ST) and goes down for 80ºC (meaning that it is less favourable for ST).
- The ratio for ST to mono is always around 88% of the ratio of ST to poly. This happens for both vacuum tubes and flat plate collectors.

6. Discussion, projections and future work

Nowadays, due to the steep decrease of the cost of PV modules, some people are arguing that ST is dead (www.GreenBuildingAdvisor.com, 2014). Although, the system simplicity, the higher value of the energy produced or the possibility to combine PV with heat pumps are very strong point for PV (Green, 1981), it is likely that ST will remain a strong and valuable energy source, especially in warm countries where the annual energy ratios are in favor of ST which is clearly shown in the figures 6, 7, 8 and 9 of this paper. Additionally, in warmer countries, the ST system design can be simpler (thermoshiphon) which has great impact for the domestic market (Ramlow, 2010).

Other favorable arguments to PV exist. The available projections expect that the cell efficiency will increase from 20% to 25% over the next five years (IEA-PVPS T1-23:2013) which correspond to a 25% output increase. Furthermore, in systems efficiency is often higher in PV than ST. On the other hand, ST benefits more from larger installation size than PV since it has benefits in both performance and cost (Ramlow, 2010). Additionally, there should be more room for a decrease in both system and production cost in ST modules than in PV, since PV has already gone down so drastically in the recent years. All in all, both PV and ST should remain in the market for years to come.

For an upcoming work, the author's plan to plot on the world map a new ratio that will be consisting of:

$$\text{Complete Ratio Between ST\&PV} = \frac{\text{Annual Energy Output per m2 of ST}}{\text{Annual Energy Output per m2 of PV}} * \frac{\text{ST colector price}}{\text{PV collector price}} * \frac{\text{typical installation cost ST}}{\text{typical installation cost PV}} * \frac{\text{typical system losses ST}}{\text{typical system losses PV}} \quad \text{(eq. 6)}$$

The annual energy ratio will favour ST while the collector price, the installation cost and the system losses should favour PV. The complete ratio would then be above 1 (favorable to ST) or below 1 (favorable to PV)

To finalize, the user should then multiply the new ratio by a ratio between the local value of heat and local value of electricity.

This ratio has the potential to become an very usefull decision tool for domestic home owners, for example.

7. References

- Wagner A., Photovoltaik Engineering, Berlin Heidelberg: Springer-Verlag, 2010.
- Wenham, S.R., Green, M.A., Watt, M.E., Corkish, R., 2007. Applied Photovoltaics, second ed. Earthscan, London. ISBN 978-1844074013
- Duffie, J.A., Beckman, W.A., 1974. Solar Engineering of thermal processes, second ed. John Wiley and Sons, Inc.
- Chen, C.J., 2011. Physics of Solar Energy. John Wiley and Sons, Inc., Hoboken, New Jersey.
- Benestad R., 2002. Solar Activity and Earth's Climate. Praxis-Springer
- Aguado E., Burt J. E, 2012. Understanding Weather and Climate. Prentice Hall PTR. 6^{th} ed. ISBN 9780321833594
- Brand, L., Calvén, A., Englund, J., Landersjö, H., Lauenburg, P., 2014. Smart district heating networks – A study of prosumers' impact on technical parameters in distribution networks. Applied Energy. 129, 39-48.

- Martin A. Green, 1981. Solar Cells Operating Principles, Technology, and System Applications. P.4, Prentice-Hall, Inc., Englewood Cliffs, N.J. 07632
- Ramlow B, Nusz B., 2010. New Society of publishers. ISB: 978-1-550-92449-7
- Climate Online, http://www.iten-online.ch/klima/europa/norwegen/bergen.htm
- "Institut für Solartechnik" http://www.solarenergy.ch/index.php?id=111&no_cache
- PVXchange, www.pvxchange.com/
- Green Building Advisor, www.GreenBuildingAdvisor.com, 2014
- IEA Trends in Photovoltaics Applications, 2013, Report IEA-PVPS T1-23:2013
- U.S. Energy Information Administration. "International Energy Outlook 2013" 2013. [Online]. Available: http://www.eia.gov/forecasts/ieo/world.cfm
- REN 21, "Renewables 2013 - Global Status Report," P.93, 2013.
- Swedish Energy Agency, "Energy in Sweden - facts and figures 2012," 2012
- Stine, W.B, Harrigan, R.W., 1986. Power from the sun. John Wiley and Sons, Inc.