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Defining an Annual Energy Output Ratio between Solar Thermal Collectors and Photovoltaic Modules

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Abstract: Photovoltaics (PV) and Solar Thermal (ST) collectors are sometimes competitors, as investment capacity, energy demand, and roof space are limited. Therefore, a ratio that quantifies the difference in annual energy output between ST and PV for different locations is useful. A market survey assessing the average price and performance both in 2013 and 2021 was conducted, showing a factor of 3 cell price decrease combined with a 20% efficiency increase, while ST showed negligible variation. Winsun simulations were conducted, and the results were plotted on the world map. Despite variations due to local climate, the ratio of energy production (ST/PV) increases at lower latitudes mainly due to (a) higher air temperature increasing ST output but decreasing the PV output; (b) solar radiation reducing ST efficiency to zero while having a minor impact on PV efficiency. The ratio was calculated for several ST operating temperatures. For latitudes lower than 66°, the ratio of a flat plate at 50 °C to a PV module ranges from 1.85 to 4.46, while the ratio between a vacuum tube at 50 °C and a PV module ranges from 3.05 to 4.76. This ratio can support the decision between installing ST or PV while combining different factors such as energy value, system complexity, and installation cost.

Keywords: annual energy output ratio; PV & solar thermal; solar electricity; solar heat; global energy scenario; decision-making tool

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1. Introduction

1.1. Energy Sector

Energy use is one of the major contributors to climate change, therefore it is necessary to convert the current energy systems to low CO_2 emitting energy sources, preferably to renewable energy systems (RES) which are sustainable in the long run.

Energy usage is often subdivided into categories such as heating and cooling, electricity, and transport. Figure 1 illustrates the shares of the different energy sources in the world's final energy consumption.

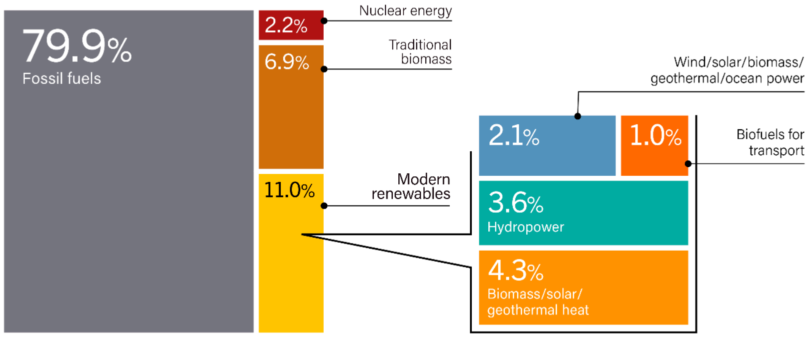


Figure 1. Estimated renewable energy share of global final energy consumption in 2018 [1].

According to the REN21 renewable energy reports, in 2009, the share of renewable energy in the total energy usage of the world was 16% [2]. In 2018, the same share was 18% [1]. In the same period, modern RES accounted for the bulk of the increase, from 6% to 11% of the world´s energy usage. Traditional biomass relevance has decreased from 10% to 7% [1,2].

A major milestone achieved is the fact that today, the world adds more RES power capacity annually than it adds in net capacity from all fossil fuels combined. This way, in 2019, RES accounted for more than 60% of all net additions to global power generating capacity [3].

By the end of 2019, RES featured 2.6 TW of power generating capacity with 1.2 TW of hydropower, 651 GW wind, 627 GW for PV, 139 GW for biopower, 14 GW of geothermal, and 6 GW of Concentrated Solar Power (CSP). Combined RES supplied over 26% of global electricity demand, with hydropower accounting for 16%, as can be seen in the following Figure 2.

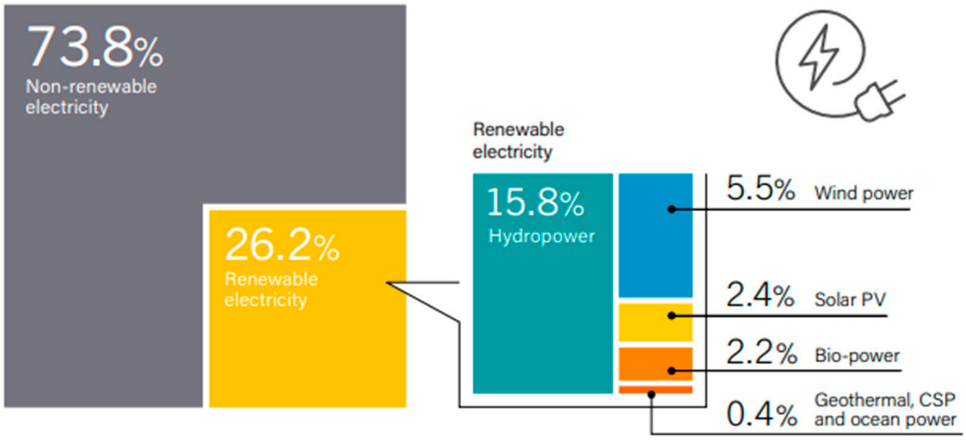


Figure 2. Estimated share of renewable energy in global electricity production in 2019 [3].

By 2040, it is expected that the cumulative growth of RES will contribute to the total primary energy consumption of 50% [4,5].

1.2. Solar Energy: PV and Thermal Collectors

Throughout history, several technologies have been developed to make use of the energy provided by the sun through its solar irradiance. This study focuses on the technologies that convert sunlight into two forms: electricity and heat.

1.2.1. Solar Electricity

Solar electricity is either produced by the photovoltaic (PV) effect or by the conversion of solar irradiation into heat which is then used to drive a turbine that generates electricity. The latter process can only be achieved with cost efficiency in large, centralized power plants such as CSP facilities.

In 2019, the total installed capacity of CSP was 5.5 GW, which compares to 505 GW of PV. As a comparison point, in 2015 alone, 100 GW of PV have been installed, which is 20 times the total installed capacity of CSP [3]. Although only 10 years ago, CSP was expected to become the mainstream solar electricity production method, PV has managed to greatly surpass CSP, having reached a total installed capacity that is 91 times higher. This is probably due to the simplicity and modularity of PV installations, which overall have much lower capital requirements than CSP. However, thermal storage can help CSP to gain momentum, as it allows CSP to do baseload and more importantly allows a shift in electricity production to the evening peaks, endowing the grid with flexibility, making it easier to incorporate additional sources of variable renewables production, such as PV. In 2016, all CSP plants were built with storage [6].

The growth in PV has been so fast that the capacity installed in the world in 2015 is nearly 10 times higher than the cumulative installed capacity registered for 2005 [5].

Figure 3 shows the top 10 countries in total installed capacity and new additions for PV solar systems, in which it can be seen that China still leads after several years. Germany has been the installed capacity leader for the last decade. However, in 2015, China took the lead [1]. In 2019, the USA became second [3], whereas India had the second-highest new additions in 2018 due to their success in scaling up solar projects [7] and policy interventions [8]. A major shift has also happened in PV production in the world. According to the REN21 2014 report: "Less than 10 years ago, almost all solar panels were produced in Europe, Japan, and the USA. In 2013, Asia accounted for 87% of global production (up from 85% in 2012) with China producing 67% of the world total (62% in 2012). Europe's share continues to fall to 9% while Japan remained at 5% and the US at only 2.6%" [1]. Experience from trends in similar technologies indicate that such global supply chains are intrinsic for a maturing technology [9].

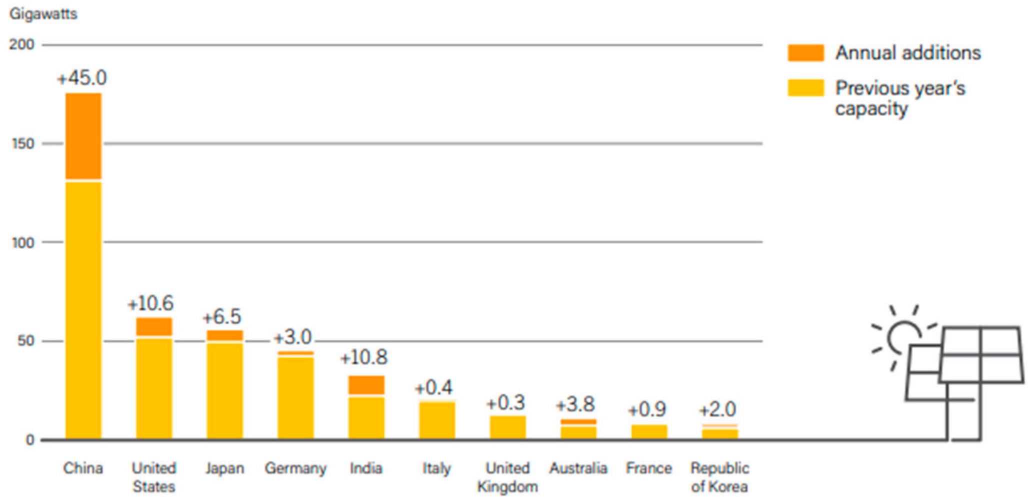


Figure 3. Installed capacity and new additions of PV in 2018 for the top 10 countries [3].

Moreover, it is important to note that several PV technologies exist with very different efficiencies and development stages. However, silicone solar cells are today the dominating PV technology with about 90% of the PV market. Within this, monocrystalline silicone cells represent about 25% of the world panel production [10–13]. It is also important to note that "Solar PV saw record additions and, for the first time, accounted for more additional power capacity (net of decommissioned capacity) than any other RES technology. Solar PV represented about 47% of newly installed renewable power capacity in 2016, while wind and hydropower accounted for most of the remainder, contributing about 34% and 16%, respectively" [6].

1.2.2. Solar Heat

Solar Heat or Solar Thermal (ST) is the process of converting solar irradiation into heat. Nowadays, there is a vast number of different technologies in existence, ranging from unglazed flat plate collectors, to vacuum tube collectors or large tracking concentrating solar collectors. These technologies produce heat at different temperatures and therefore have multiple applications in residential and industrial sectors.

Figure 4 shows the total installed capacity in 2018 of solar heating in the world at 480 GW_{th}. For reference, it can be compared to the installed capacity of PV with 505 GW_e [3]. However, it is fundamental to keep in mind that, when comparing PV and ST, they have different annual capacity factors and produce energy with different values. For instance, the 456 GW_{th} of ST in 2016 are estimated to have produced 375 TWh of heat at different temperatures. At the same time, the 303 GW of PV produced about 375 TWh of electricity [6].

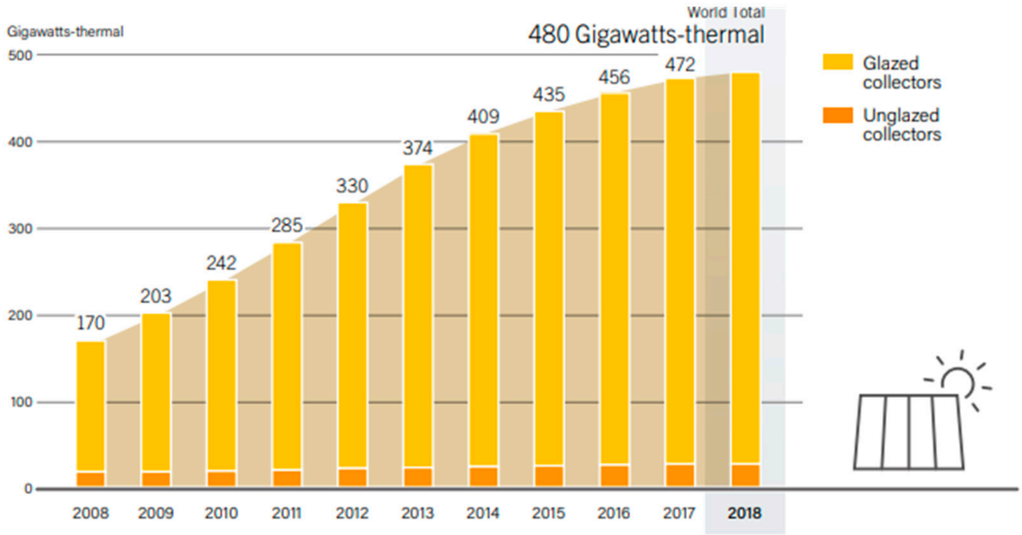


Figure 4. World installed capacity of ST in 2018 [3].

In 2017, China accounted for 75% of the total new worldwide additions. The Chinese market has been undergoing a change from small residential to large installations such as hotels or the public sector [2]. In 2018, the installed capacity of ST collectors grew by 1.7% (8 GW_{th}) which is a significant growth reduction from previous years. As a comparison point, the installed capacity of PV is record-breaking, as it grew by 25% which corresponds to 100 GW [3]. Over the last 10 years, the total installed capacity of ST has roughly quadrupled while PV has been multiplied by a factor of 33. However, although there is a difference of an order of magnitude between these two numbers, it is important to point out that PV started with a much lower base number from which it was easier to increase. Figure 5 shows how China is currently dominating the solar market.

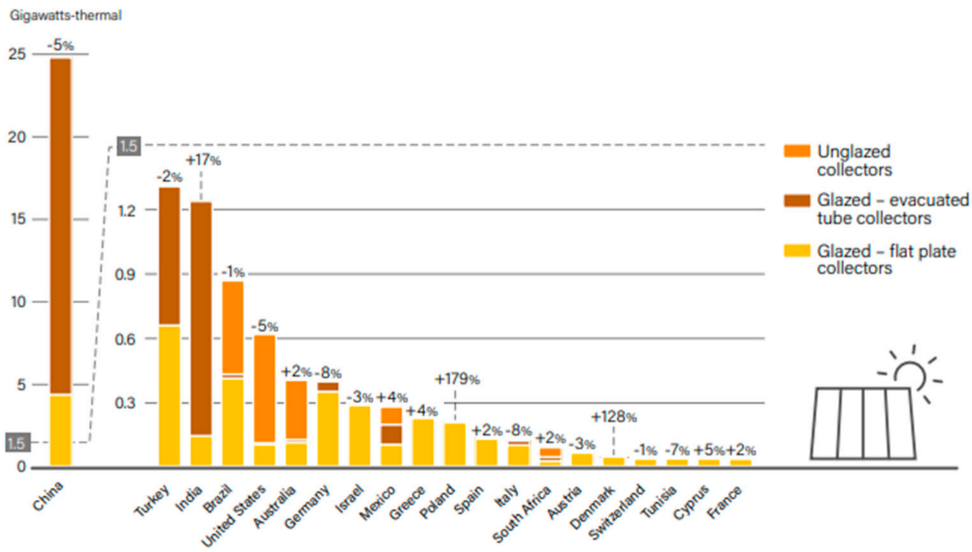


Figure 5. Installed capacity of ST in the top 20 countries in 2018 [3].

Finally, it is important to acknowledge that the heat produced by a ST collector can serve different purposes, as shown in Figure 6.

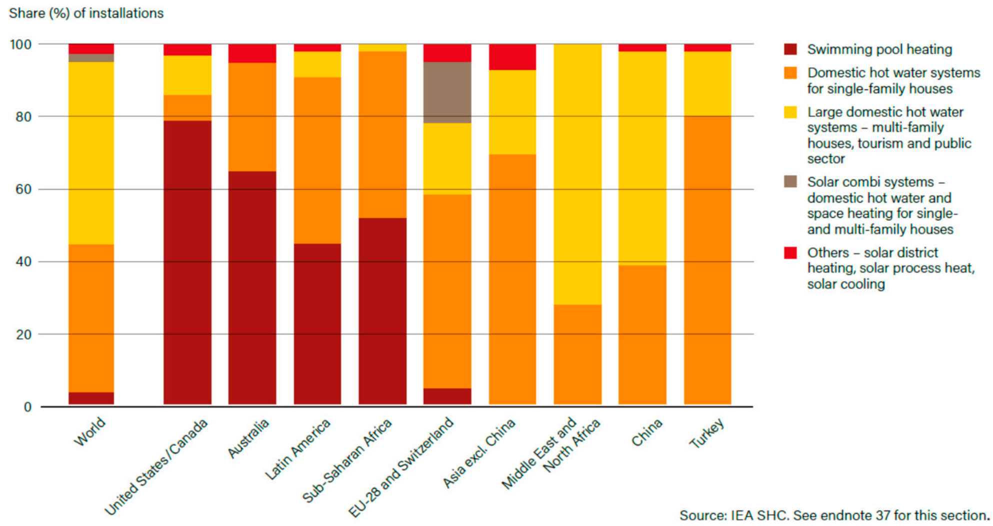


Figure 6. Solar thermal applications by economic region in 2015 [14].

Globally, Domestic Hot Water (DHW) production, either for single or multi-family houses, is the main application for ST, although some economic regions install ST for different purposes.

1.3. Background on Comparing Heat and Electricity

Energy has many forms such as heat and electricity and comparing these different forms is not straightforward. Exergy or the quality of energy is of high relevance when discussing primary energy.

According to Carnot, if the reference temperature is 0 °C, heat at 75 °C can theoretically be converted to power with the following efficiency.

$$\eta = 1 - \frac{273}{273 + 75} = 0.216 \quad (1)$$

$$1\ \mathrm{kWh_{electricity}} = \frac{1}{0.216} = 4.64\ \mathrm{kWh_{heat}} \quad (2)$$

Similarly, according to Carnot, 1 kWh of electricity can be converted to heat at 75 °C with a heat pump.

$$\mathrm{COP} = \frac{T_{high}}{T_{high} - T_{low}} = \frac{273 + 75}{75} = 4.64 \quad (3)$$

$$1\ \mathrm{kWh_{el}} = 4.64\ \mathrm{kW_{heat}} \quad (4)$$

Equation (4) can be explained by a COP = $1/\eta$. However, in real systems, the COP is well below $1/\eta$. This means that the ratio between the values have different magnitudes, depending on the direction of conversion. This is one of the reasons why it is so difficult to define the values of primary energy factors.

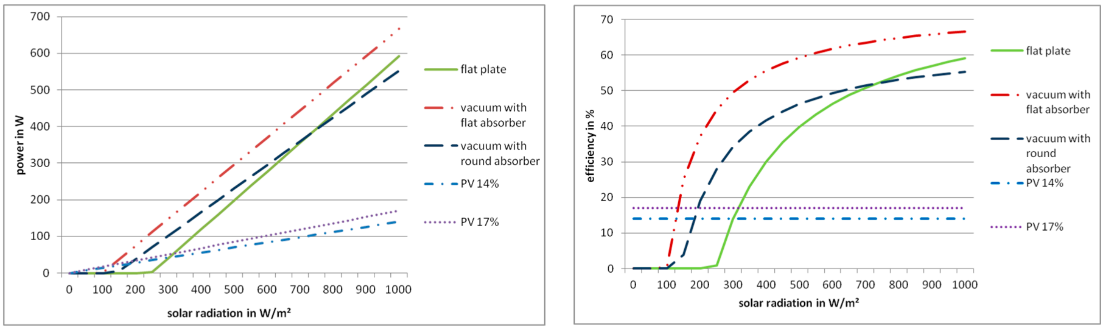
1.4. The Effect of Solar Radiation on the Power and Efficiency of PV and ST Collectors

Figure 7 shows the effect of solar radiation on both power output and efficiency for PV panels and ST collectors which is calculated according to a simplified model using the following formulas:

$$\text{PV modules}: \ P = I \cdot \eta \quad (5)$$

$$\text{ST collectors}: \ P = \eta_0 \cdot I - ((U_1 + U_2 \cdot \Delta T) \cdot \Delta T) \quad (6)$$

where P is the power from the collector, I is the irradiance on the plane, η is the efficiency of the collector, η_0 is the optical efficiency of the thermal collector, U_1 is the first order heat loss coefficient, and U_2 is the second-order heat loss coefficient. Figure 7 shows a graphical representation of the above formula.



(**a**) (**b**)

Figure 7. The impact of solar radiation on power (**a**) and efficiency (**b**) for both PV and ST (at 50 °C).

The collector values used to plot the above graphs were taken from a market survey conducted by our team and shown below. These efficiency values are for a standard thermal collector and are calculated based on the aperture area of collectors operating at a temperature of 50 °C, where $T_m = (T_{in} + T_{out})/2$. In this model, only the most relevant factors are taken into consideration. In reality, there are other factors to consider, such as a small efficiency dependence of Si solar cells on irradiation levels and spectral distribution [15] or an increase in the temperature of the solar cells that leads to a decrease in solar cell efficiency of around −0.35 %/K for monocrystalline solar cells [16]. However, Figure 7 shows that, at a constant temperature, the efficiency of a PV system is almost independent of the solar irradiance, while the efficiency of solar thermal systems is strongly dependent on the efficiency of a thermal collector often being zero at low solar radiation intensities.

Another important point to mention is that system losses such as inverters, cabling, or piping were not considered, either for ST or for PV.

1.5. The Effect of Temperature on the Efficiency of PV and ST Collectors

Figure 8 shows the effect of operating temperature on the efficiency of the solar panels and was calculated using Equations (5) and (6). For the PV panels, the cell temperature dependency was considered as described below.

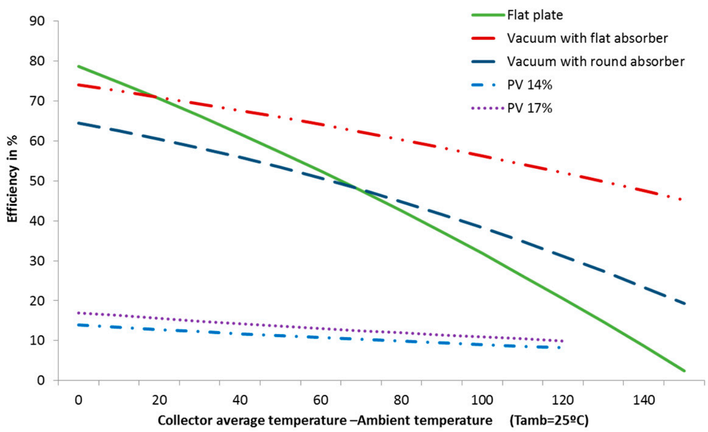


Figure 8. The impact of temperature on efficiency on PV & ST panels at constant solar radiation of 1000 W/m^2.

The operational temperature of a PV panel varies according to how much solar radiation is received and how much heat the panel dissipates, 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). In Figure 8, it was accepted that 120 °C was the maximum temperature for the PV panel since many panels stop working above that temperature due to the limitations of Ethylene Vinyl Acetate (EVA), which is the standard encapsulation method for solar cells in PV [17]. Similar to PV panels, the operational temperature of an ST collector is also a function of solar irradiation and heat losses, however, in ST systems there is also a fluid used for extracting heat from the solar collector. This fluid can be water, glycol, or a special type of oil for collectors that work at very high temperatures. The amount of heat that is transferred to the fluid depends on factors such as the temperature difference between the fluid and the collector, the ambient temperature, the characteristics of the fluid, the speed, and flow type [18].

A major difference between PV and ST panels is that, in ST panels, the heat is carried away from the collector to the tank, while in standard PV panels the built-up heat is passively dissipated. A similarity of both types of panels is that the efficiency goes up when the operating temperature is decreased.

1.6. Influencing Factors: Local Climate

Weather conditions vary widely around the globe. As an example, Figure 9 shows the variation of beam irradiation around the world while Figure 10 shows the annual average temperature. Many other parameters, such as the median daily variation of temperature or the air humidity could be shown to illustrate these large variations. The numbers in Figure 9 show the percentage of beam irradiation out of the total solar irradiation normal to the ground, while the color shows the total amount of solar radiation. As can be observed in Figure 9, the beam fraction is not dependent on the latitude although the total amount of solar irradiation generally increases at lower latitudes. The main influence on the beam fraction is the local climate [19].

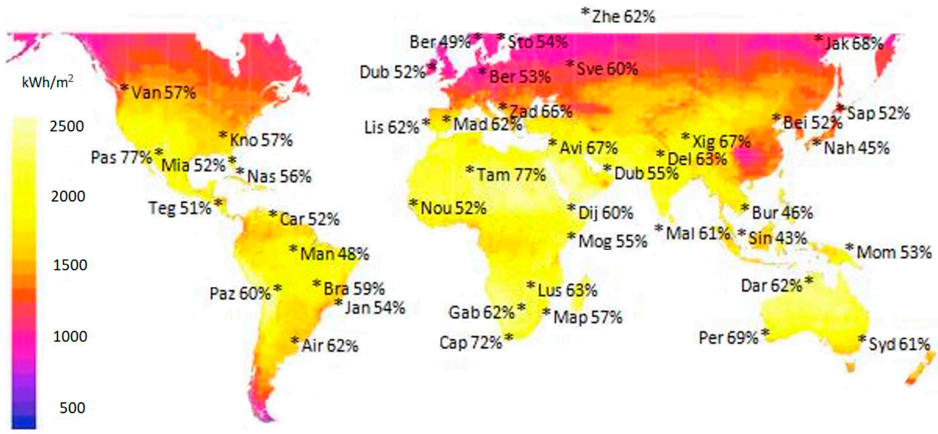


Figure 9. Percentage of beam radiation in the total solar radiation at latitude tilt (number) and total solar radiation in different locations (color). Data source: Meteonorm and Winsun.

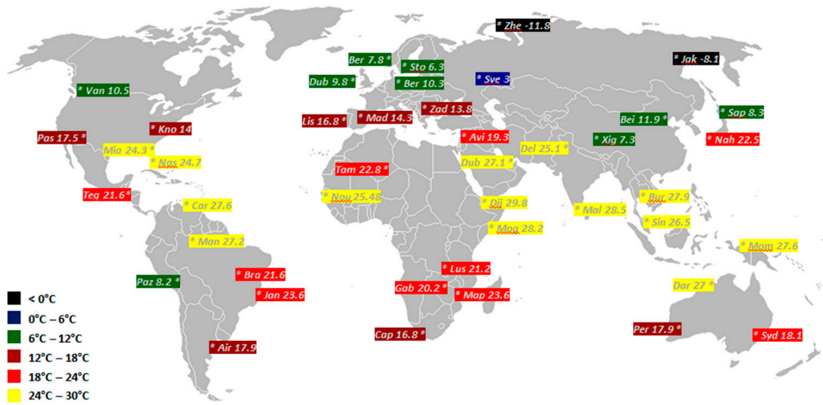


Figure 10. Annual average temperature of 66 cities around the globe. Meteorological data source: Meteonorm.

The percentage of beam irradiation in the total irradiation ranges from 43% in Singapore to 77% in El Paso and Tamanrasset. Singapore, Naha, Chon Buri, Manaus, and Bergen are the only five cities where the diffuse irradiation represents more than 50% of the annual solar irradiation at 0° tilt. The main reason for this effect is the presence of clouds [20]. Cities in Southeast Asia are affected by the monsoon, twice a year. Bergen has 200 rainy days over the year and a moderate climate [21]. Manaus, located close to the equator, is affected by a long rainy season which leads to 48% of the beam radiation in the total solar radiation. However, in desert areas like El Paso or Tamanrasset, the climate is dry, and the ratio reaches up to 77%. As expected, the countries closer to the equator show the warmest average temperatures around the world which go up to 30 °C. However, there are exceptions like La Paz with 8.2 °C which owes its low annual temperature to the high altitude. At high altitudes, the layer of the atmosphere is less dense which leads to both higher temperature variations (the atmosphere has less capacity to retain the heat) and higher solar irradiation (the atmosphere is less dense and absorbs less solar irradiation). The main cause of low temperatures at higher latitudes is the angle at which the incoming rays hit the ground. Although the solar irradiance on a perfect sunny day is close to 1000 W/m^2 anywhere in the world at sea level, if the irradiance has a lower angle, that irradiance will be spread over a larger area. This effect is also known as the cosine effect [20].

Locations with the same annual temperature may present very different temperature profiles. For example, Lisbon and El Paso have similar annual temperatures (around 17 °C). However, when comparing the daily profile, it can be found that the temperature is steady in Lisbon, a coastal city with a Subtropical–Mediterranean climate. Conversely, El Paso has large variations over 24 h and a hot desert climate. Another example is the climate on the West Coast of Europe. It is much milder than the climate in the interior of Europe at the same latitude. This is due to the effect of the Gulf Stream that not only warms up the air but also stabilizes its temperature [22].

Moreover, this manuscript aims at providing a performance ratio dependent on where a PV or ST solar system is installed. This ratio aims at supporting the decision holders to better understand the differences between technologies and therefore the best fit for each location.

2. Definition of the Ratio between ST and PV

Although PV and ST produce different types of energy, they are often competing among themselves. This is not only because the investment capacity is limited, but also because of other limiting factors such as energy demand and roof space. Additionally, electricity can be converted into heat and vice versa. However, electricity can be converted into heat at an efficiency of almost 100%, heat conversion in electricity has much lower efficiency and requires more complex equipment [23].

The previously described large global climate variations lead to significant differences in the performance of solar systems around the globe. Moreover, each type of solar system 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 can be useful, for example, to support the decision between installing ST or PV, when combined with other local information such as the value of heat and electricity for a specific location and application, the system complexity and efficiency, and even factors such as the knowledge of local installers or the available offer. This way, the ratio was defined, as follows:

$$\text{Ratio Between ST and PV} = \frac{\text{Annual Energy Output per m}^2\text{ of ST collector}}{\text{Annual Energy Output per m}^2\text{ of PV panel}} \quad (7)$$

This ratio was calculated for the different solar systems based on the results obtained from a market analysis. Two types of PV panels were considered: average monocrystalline and polycrystalline panels. Two main types of ST panels were considered: Flat Plate and Vacuum Tube. Additionally, for ST collectors, the following average collector temperatures were investigated: 30 °C, 50 °C, and 80 °C. The reason for the selection of these three temperatures is that they constitute the lower, middle, and upper range of the adequate operating temperatures for glazed flat plates and vacuum tube collectors.

The annual energy outputs used to calculate the above ratio were obtained through Winsun simulations.

This ratio was then calculated and plotted on the world map for clear visualization. The three above mentioned temperatures were plotted but only the middle temperature (50 °C) is shown since it is the most used working temperature in solar applications, especially for domestic hot water. Additionally, it was also in the middle of the range of the selected fluid temperatures, and the authors felt that selecting 30 °C would yield a too favorable view of ST while selecting 80 °C would yield a too favorable view of PV.

3. Market Survey

A detailed two-step market survey was carried out to investigate the prices and average panel characteristics for both PV and ST. The first assessment was carried out in 2013, while the second step was carried out in 2021. The ST survey included a total of 90 collectors of three types: flat plate, vacuum tube with flat absorber, and vacuum tube with a circular absorber. This survey comprised 43 companies in 16 countries. All collectors in this study have undergone testing under the standard EN 12975 and an arithmetic average of the test results was made based on the available data from the solar Keymark website. This average is displayed in the following Table 1.

Table 1. Performance values for different ST collectors expressed per absorber, aperture & gross area.

Type of Panel	Absorber			Aperture			Gross		
	η_0 (%)	U_1 (W/m^2K)	U_2 (W/m^2K^2)	η_0 (%)	U_1 (W/m^2K)	U_2 (W/m^2K^2)	η_0 (%)	U_1 (W/m^2K)	U_2 (W/m^2K^2)
Flat Plate	80	4.0	0.009	78	3.9	0.008	71	3.5	0.008
Vacuum with round absorber	74	2.1	0.009	64	1.8	0.008	40	1.1	0.005
Vacuum with flat absorber	82	1.6	0.004	74	1.5	0.003	55	1.1	0.003

The PV survey investigated 150 different PV panels from 35 companies from 9 countries. Additionally, the 10 largest cell manufacturers were also analyzed, and the average efficiency is shown in Table 2.

Table 2. Average efficiency for monocrystalline and polycrystalline panels and cells (2021).

	Efficiency in 2013		Efficiency in 2021		Efficiency Increase	
Type of PV Panel	Cell	Panel	Cell	Panel	Cell	Panel
Monocrystalline	18.9%	16.4%	22.2%	20.2%	18%	22%
Polycrystalline	16.5%	14.6%	19.5%	17.7%	18%	21%

Finding out the price of the ST and PV panels at the customer level proved to be a more complex process than expected and some uncertainty lingered, as the price variations between obtained quotes were considerably large. Another important factor to consider is the size of the order, as prices tend to go down with larger volumes. In the present market study, the ST quotes were obtained for an order size of two panels, while for PV the size was 50 panels. Although not ideal, this situation occurred due to limited access to quotes from a large number of solar PV and ST suppliers. The following Tables 3 and 4 describe the prices that were found in the market study.

Table 3. Price of a ST collector in € per gross and aperture area (installed price).

Type of ST Panel	Flat Plate		Vacuum Tube (Flat Absorber)		Relative Difference FP to VT	
	2013	**2021**	**2013**	**2021**	**2013**	**2021**
Sale with VAT (consumer) in €/m^2 gross	158	141	166	154	5%	9%
Sale with VAT (consumer) in €/m^2 aperture	187	167	275	255	32%	34%
Relative difference gross to aperture area	15%	15%	40%	40%	-	-

Table 4. PV price from cell to panel in €/W_p (not including system & installation).

	Cost in 2013 (€/W_p)		Cost in 2020 (€/W_p)		Price Decrease	
Type of PV Panel	**Poly**	**Mono**	**Poly**	**Mono**	**Poly**	**Mono**
Cell Price	0.27	0.31	0.09	0.12	0.27/0.09 = 3	0.31/0.12 = 2.6
Panel sale price including VAT	0.52	0.56	0.17	0.21	0.52/0.17 = 3	0.56/0.21 = 2.5
Price increase from cell to panel	1.9	1.8	1.9	1.8	-	-

In Table 5, the costs of system components, installation, and VAT are shown for the Swedish market (both for PV and ST).

Table 5. Price comparison of PV to ST (including system components, installation, and VAT) at the consumer level in the EU (Sweden, custom cleared).

Type of Solar Panel	Price €/m^2 Aperture		Comparison to Poly		Comparison to VT	
Year	**2013**	**2021**	**2013**	**2021**	**2013**	**2021**
ST Flat Plate	187	167	61%	67%	68%	65%
ST Vacuum Tube with flat absorber	275	255	89%	102%	100%	100%
PV Polycrystalline	282	212	100%	100%	103%	83%
PV Monocrystalline	308	250	91%	85%	112%	98%

The survey shows that in a space of less than eight years, the efficiency of PV cells and panels has increased by roughly 20%. More striking is what happened in terms of price on both PV panels and cells, which have both gone down drastically in terms of €/W_p. This is a factor 3 reduction for polycrystalline and around 2.6 for Monocrystalline cells. Monocrystalline cells enjoy a higher market demand, and this might be the reason why the reduction is less pronounced for monocrystalline when compared to polycrystalline. It is also important to point out that the PV price reduction on a per m^2 basis is not so pronounced as in €/Wp, as the increase in efficiency offsets partially the cost reduction in €/W_p. Both the cost reduction and efficiency increase for ST is far less pronounced.

4. Simulation

Winsun is a TRNSYS-based solar simulation software that was developed by Bengt Perers and Björn Karlsson at Lund University. Winsun can simulate both the annual performance of an ST and PV panel. The inputs and outputs of the program are described in Figure 11.

A new collector file was made for Winsun based on the market survey findings regarding the standard collector characteristics per aperture area. The values for efficiency and heat losses were taken from the market study and are presented in the results. 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 to obtain a better visualization of the variation of the ratio in the world map.

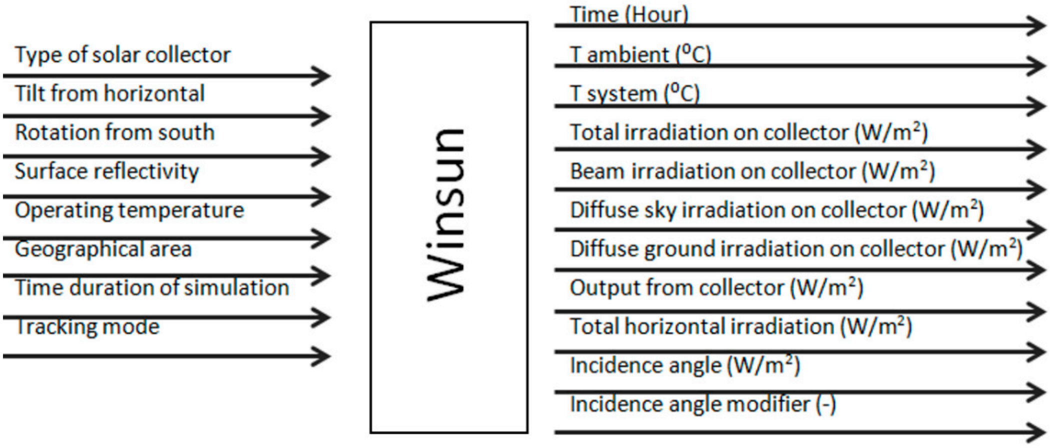


Figure 11. Winsun's necessary inputs (**left**) in order to provide the required outputs (**right**).

Winsun was used to simulate the performance of PV and ST panels over the year and provide the annual output per m^2 of aperture area. The following formulas from Duffie [18] are used by the Winsun to calculate the annual output:

$$Q = \eta_{0b} \cdot K_b(\theta) \cdot G_b + \eta_{0b} \cdot K_{diffuse} \cdot G_d - U_1(T_m - T_a) - U_2(T_m - T_a)^2 \quad (8)$$

$$K_b(\theta) = 1 - b_0 \cdot \frac{1}{\cos(\theta) - 1} \quad (9)$$

The PV model that is used by Winsun has the limitation of having no temperature dependence, which will affect the results. Nevertheless, this limitation will not influence significantly the results presented in the following sections. Therefore, the PV model implemented in the simulation software is fairly similar to the thermal model presented in Equations (8) and (9), with the minor condition that $U_1 = U_2 = 0$. A new collector file was made for Winsun based on the market survey findings regarding the standard collectors' characteristics per aperture area. Climate data files, including temperatures and solar radiation, were created for a total of 66 cities. These climate data files were based on information available from the software Meteonorm. For all performed simulations, the collector was stationary at a tilt equal to the latitude of the selected city, which allows obtaining an output close to the maximum possible. These values are fed into Equations (8) and (9) to obtain the annual output for a given collector at a given temperature and location.

Simulations were performed for two PV and three solar thermal technologies at three different temperatures for the 66 selected cities around the world, in a total amount 726 simulations. This allowed obtain a better visualization of the variation of the ratio in the world map under a wide range of different latitudes and climatic regions.

5. 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. An ST panel always yields more energy than PV when placed in all locations at a temperature of 50 °C. As expected, this is also true for an ST operating temperature of 30 °C. However, at an operating temperature of 80 °C, there were two locations in this study (in Russia and Norway) where the flat plates performed worse than PV. Unlike flat plates, vacuum tube collectors performed better than PV in all simulated locations and temperatures. This was due to a lower heat loss factor. Additionally, globally, vacuum tubes normally outperform flat plate collectors per aperture area for temperatures of 50 °C and 80 °C. However, for a temperature of 30 °C, the flat plate sometimes outperformed the vacuum tube with a flat absorber, especially in warm locations. This is since flat plates have 5% higher peak efficiency.

The ratio between PV and ST ratio was then plotted on a world map for clear visualization. The temperature of 50 °C was selected to be plotted. This way, four world maps were created. The maps show how much more energy ST produces compared to PV. In general, the ratio increases when the latitude decreases. Some examples of this ratio are shown in Table 6 for three cities at three 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 (°)	Solar Radiation (kWh/m^2)		Output (kWh/m^2)				Ratio			
		Total	Beam	Poly PV	Mono PV	Flat Plate	Vacuum Tube	Flat Plate to Poly PV	Flat Plate to Mono PV	Vacuum Tube to Poly PV	Vacuum Tube to Mono PV
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 Table 6, the ratio between a flat plate working at 50 °C and a polycrystalline PV panel varies considerably around the world. In Nairobi, a flat plate will produce 3.7 times more energy than a polycrystalline PV panel 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.

All legends have the same scale for Figures 12–15. The scale goes from green (stronger ST location) to blue (weaker ST location). The black color is an extreme case, which only happens in two specific situations in northern Russia.

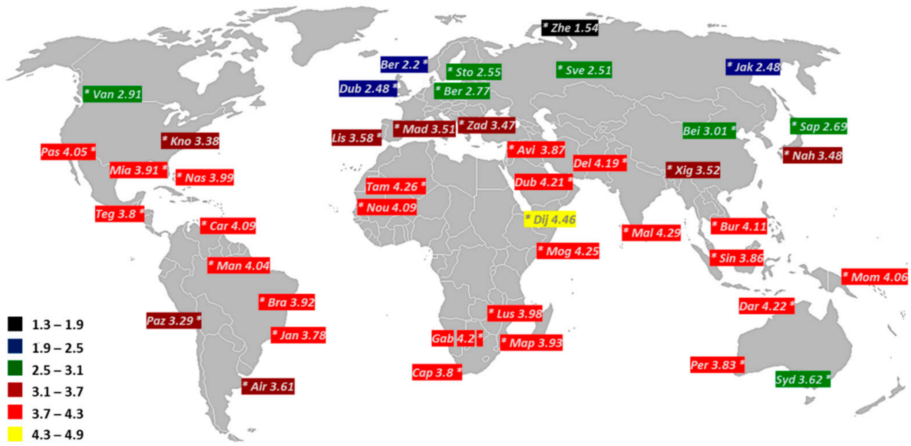


Figure 12. Ratio of flat plate 50 °C to PV polycrystalline.

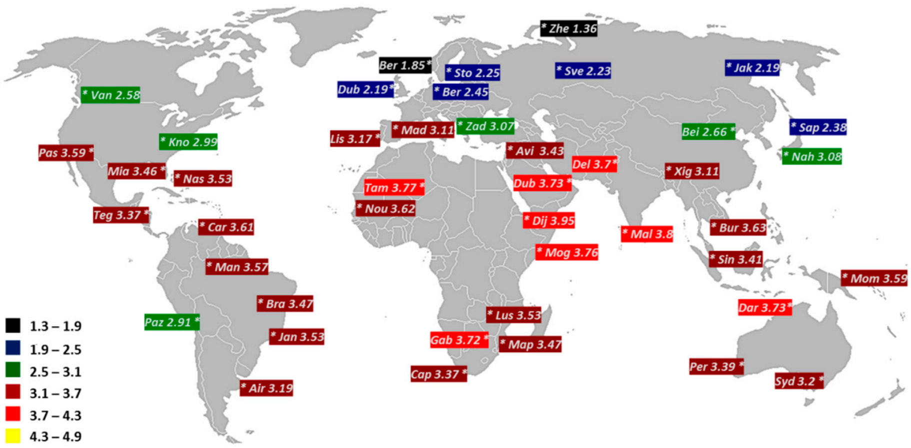


Figure 13. Ratio of flat plate 50 °C to PV monocrystalline.

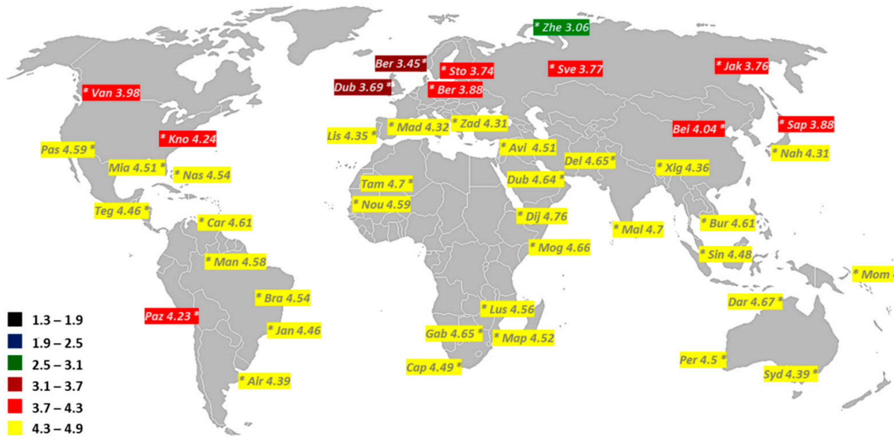


Figure 14. Ratio of vacuum tube with flat absorber 50 °C to PV polycrystalline.

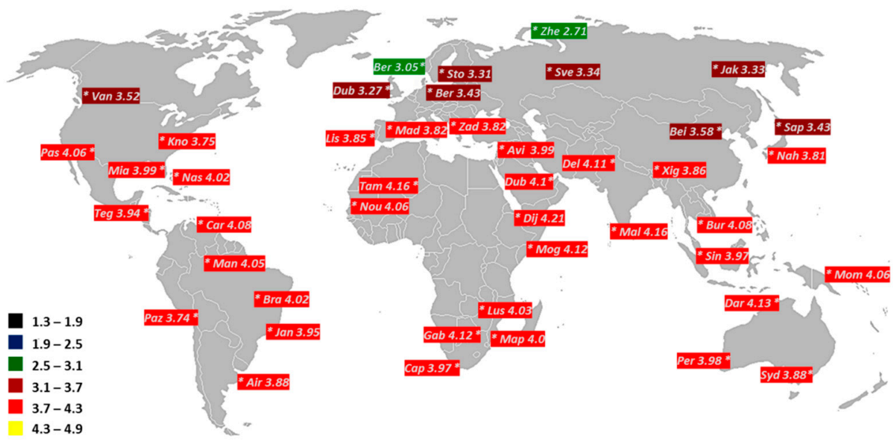


Figure 15. Ratio of vacuum tube with flat absorber 50 °C to PV monocrystalline.

Figure 12 shows the ratio between a flat plate collector working at an average temperature of 50 °C and a polycrystalline module. The lowest ratio of 1.36 is found in Figure 13 the coldest place with the highest latitude. On the opposite end, the city of Djibouti, latitude of 12°, reaches a ratio of 4.46, which signals an over-performance of ST compared with 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, cloudy rain season, which also lowers the ratio of the beam to total irradiation as shown previously. All four maps show that for locations with high diffuse irradiation or low ambient temperature, the ratio decreases which means that ST is producing less energy in comparison with PV.

Figure 13 shows the annual energy output ratio between flat plate working at 50 °C and monocrystalline PV. The ratios in Figure 13 are lower than in Figure 12 since monocrystalline modules have a higher efficiency than polycrystalline. The ratio of ST to monocrystalline is always around 88% of the ratio of ST to polycrystalline. This happens for both vacuum tubes and flat plate collectors.

As expected, the ratio between the vacuum tube with a flat absorber and the polycrystalline modules shows the highest values in all four maps. For an ST working temperature of 50 °C, the highest ratio value was found to be 4.76 in Djibouti, a city located close to the equator with a warm average temperature of 30 °C [22]. The lowest ratio in Figure 14 is 3.06, which is considerably higher than the lowest ratio found in Figure 12 which shows the ratio between flat plate and polycrystalline PV, which is 1.54. This is mainly explained by the extremely low temperatures in this location combined with the fact that vacuum tubes have lower heat losses than standard flat plates. In between latitudes of 40° N and 40° S, all ratios in Figure 14 are above 4.2.

Figure 15, out of Figures 12–15, has the smallest variation between the highest and lowest ratio, which is 1.5. The highest ratio found was 4.21, which is lower than the highest ratio between flat plate to polycrystalline PV which is 4.46. In all maps, the lowest ratio is always Cape Zhelaniya (Russia) while the highest ratio on the graph is in Djibouti.

6. Conclusions

A two-step market survey was conducted that determined the average performance and price values for various types of ST and PV panels. From 2013 to 2021, PV cell efficiency increased by 20% and the cost reduction on a €/W basis decreased by a factor of 3 for polycrystalline cells and a factor of 2.6 for monocrystalline cells. PV panels have followed similar trends. Both the efficiency improvement and cost reduction on solar thermals show in comparison a negligible improvement during the same time-period. The performance values obtained from the survey were then used to simulate the annual energy output of each type of panel using the TRNSYS-based software Winsun. This was the basis for establishing a qualitative comparison between ST and PV panels, the annual energy output ratio. To ease the interpretation of those results, several world maps were drawn to graphically display the differences in annual energy production of the different solar technologies in different locations.

On a world scale, this ratio tends to increase at lower latitudes, which is visible in Figures 12–15. This happens despite large variations being introduced by the local climate. The higher ratios at low latitudes mean that ST panels are performing comparatively better than PV. At higher latitudes, the ratio generally reduces meaning that ST performance in comparison with PV is less strong. Two main factors are responsible for this:

- The efficiency of a PV panel is reduced with the increase of air temperature while in solar thermal the opposite effect takes place.
- Under low-intensity solar irradiance, the efficiency of a PV panel is maintained while a solar thermal collector might not reach the required operating temperatures and have an output of zero.
- The ratio maps allow reaching the following conclusions:
- For all locations and a working temperature of 50 °C, the ST panel always yields more energy than a PV module.
- Vacuum tubes with flat absorbers normally outperform flat plate collectors per aperture area for temperatures of 50 °C and 80 °C. However, the price per aperture area of a vacuum tube with a flat absorber is also 32% higher than a flat plate. This means that by assuming the installation cost is the same for both ST technologies, vacuum tubes should be preferred only if the annual output is higher than a flat plate annual output by 32%.
- For a temperature of 30 °C, the flat plate sometimes outperforms the vacuum tube with a flat absorber, namely in warm locations.
- All four maps show that for locations with high diffuse radiation or low ambient temperature, the ratio decreases, meaning that ST is producing less than a PV module.
- For latitudes lower than 66°, the ratio of a flat plate at 50 °C to PV ranges from 1.85 to 4.46 while the ratio between a vacuum tube at 50 °C and PV ranges from 3.05 to 4.76. These numbers can be an important tool when deciding between PV and ST. However, it is important not to forget that dimensioning of ST installations is of utmost importance to ensure that there is sufficient heat demand so that the collectors are working at a high efficiency, which is key to generating good revenue.
- The ratio was also calculated for ST operating temperatures of 30 °C and 80 °C. As expected, the ratio goes up for 30 °C (meaning that it is more favorable to ST) and goes down for 80 °C (meaning that it is less favorable for ST).
- The ratio for ST to monocrystalline is always around 88% of the ratio of ST to polycrystalline. This happens for both vacuum tubes and flat plate collectors.

7. Discussion, Projections and Future Work

Nowadays, due to the steep decrease in the cost of PV modules, there are discussions regarding the competitiveness of ST [24,25]. Although the simplicity of the system, the higher value of the energy produced or the possibility of combining PV with heat pumps are very strong arguments in favor of PV [26], ST will likely remain a strong and valuable energy source, especially in warm countries where the annual energy ratios are more strongly in favor of ST, which is clearly shown in Figures 12–15 of this paper. Additionally, in warmer countries, the ST system design can be simpler (thermosiphon) which has a great impact on the domestic market [27]. This paper provides a metric to support such investigations.

Still, other favorable arguments for PV exist. Presently, there are commercially available PV back contact Si modules that have efficiencies of around 24% [28] and this novel technology will become mainstream in the coming years [29]. Furthermore, the system's losses are often lower for PV than ST. On the other hand, ST benefits more from a larger installation size than PV, since it has benefits in both performance and cost [27]. Additionally, there should be more room for a decrease in the costs of system equipment and panel production in ST modules, when compared with PV, since PV cost has already decreased by 90% since 2009 [30] due to larger production volumes and heavy research investment.

There has also been research into the merits and possibilities of exporting solar thermal electricity from tropical regions to elsewhere such as from Northern Africa to Europe [31]. According to the European Solar Thermal Technology Platform, energy consumption worldwide is divided into 20% electricity, 30% transport, and 50% heating and cooling. Although there is a current trend for electrification (i.e., electric cars), when taking a holistic approach, the authors consider that it is not a good idea to use electricity to produce low-temperature heat, as there are more efficient alternatives for this segment than for other energy segments. Furthermore, enlarging the grid is costly and time-consuming and it is not likely that the world will manage to build an electricity grid that can cope with an electrical consumption that is five times as high. Furthermore, ST is expected to become an essential complement to achieve net-zero emission targets [32]. Thus, it is the authors' opinion that both ST and PV technologies will continue to co-exist in a very competitive market, as both technologies are essential to meet climate targets and have specific advantages and disadvantages. Nevertheless, it is very important to state that a substantial amount of energy is typically generated during the day, when the demand does not meet energy production. This fact is not related to system or solar collector efficiency but solely to its effectiveness.

For instance, in extremely hot weather, typically, there is a high electrical demand but not for thermal heat since much of the cooling is electrical. However, the demand patterns could change as technology evolves, for example, developments in thermally driven cooling systems, particularly in the cost of these systems, could change the market significantly. Regardless today, overproduction during the summer period when there is an insufficient demand, remains a significant issue for ST collectors. This often leads to the deployment of smaller systems and consequently the coverage of a smaller fraction of the energy needs of the costumer.

For an upcoming work, the authors plan to plot on the world map a new ratio that will consist of:

$$\text{New Ratio} = \frac{\text{Annual Energy Output per m}^2\text{ of ST}}{\text{Annual Energy Output per m}^2\text{ of PV}} \times \frac{\text{ST colector price} + \text{installation cost ST} + \text{system cost}}{\text{PV collector price} + \text{installation cost PV} + \text{system cost}} \times \frac{\text{avg system losses ST}}{\text{avg system losses PV}} \tag{10}$$

The annual energy ratio will favor ST, while the collector price, the installation cost, and the system losses should favor PV. The complete ratio would then be above 1 (higher ST output) or below 1 (higher PV output). To finalize, the user should then multiply the new ratio by an additional ratio which considers the local value of heat and electricity. Furthermore, this ratio should be created for a few typical installation types and technologies, similar to what has been done in this manuscript. The authors believe that this ratio has the potential to become a useful decision tool for domestic homeowners, for example.

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Abbreviations

Photovoltaic	PV
Power from the collector	P
Concentrated Solar Power	CSP
Solar Thermal	ST
Solar thermal power	Q
Nominal Operating Cell Temperature	NOCT
Value Added Tax	VAT
Renewable Energy System	RES
Coefficient of Performance	COP
Ethylene Vinyl Acetate	EVA
List of Units	
Cost per unit area	€/m^2
Cost per unit of power	€/W$_\mathrm{p}$
Electrical production	Wh_e
Power from photovoltaic	W_e
Thermal production	Wh_{th}
Power from solar thermal collectors	W_{th}
Temperature	°C
Heat transfer coefficient	W/m^2·K or W/m^2·K^2
Efficiency	η
Temperature from the hot side	T_{high}
Temperature from the cold side	T_{low}
Ambient temperature	T_a
Irradiance on the collector plane	I
Optical efficiency	η_0
Optical efficiency for beam radiation	η_{0b}
First-order heat loss coefficient	U_1
Second-order heat loss coefficient	U_2
Temperature difference between inlet and outlet	ΔT
Mean fluid temperature	T_m
Inlet temperature	T_{in}
Outlet temperature	T_{out}
Incidence angle modifier coefficient for beam radiation	K_b(`)
Incidence angle modifier coefficient for diffuse radiation	K_{diffuse}
Diffuse radiation	G_d
Beam radiation	G_b
Incidence angle modifier coefficient	b_0

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