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COMPUTING THE EXERGY OF SOLAR RADIATION FROM REAL RADIATION DATA ON THE ITALIAN AREA

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ABSTRACT

The decrease of fossil fuels availability and the consequent increase of their price, has led to a rapidly evolution of renewable market and policy frameworks in recent years. Renewable resources include solar radiation which is of considerable interest as it is inexhaustible, free and clean. In order to calculate how much work can be obtained from solar radiation, several methods have been proposed in the literature. The aim of this work has been to calculate the exergy content of solar radiation in Italy. To do this, we have analyzed real radiation data and we have treated direct and diffuse radiation separately. We have proposed a single exergy factor valid on the Italian area, which is to be applied to the total radiation measured on horizontal surface.

INTRODUCTION

Renewable resources include solar radiation which is of considerable interest as it is inexhaustible, free and clean. Since it is intermittent, diluted and not evenly distributed on the Earth surface, systems that exploit solar energy are almost always coupled with ones that use fossil fuels. This coupling set up the so called hybrid systems which ensure consistent performance over time. Solar radiation exploitation is divided into capture, conversion into another kind of energy (for example electricity or work) and storage. In this article only the passage through the atmosphere is analyzed, with the aim to determine the exergy content of solar radiation. Governments encourage the development of hybrid systems through incentives: their payment is based on the fraction of the produced power that is allocated to renewable resources, as explained in [1]. One aspect that still causes uncertainty is the allocation of solar radiation energy, more precisely the computing of solar radiation exergy content. Exergy represents the maximum work obtainable from a system or a process in a given environment. Unlike energy, exergy is not conservative, and it gives information about the room for improvement of a process. In the literature, various models have been proposed for computing solar radiation exergy: the studies began considering black-body radiation, then considering the radiation spectral distribution, up to consider the radiation components - direct and diffuse - separately. Also the assumption of thermodynamic models representative of the phenomena in the atmosphere to which solar radiation undergoes changed in the course of scientific research. The aim of this article is to determine a reference value for computing solar radiation exergy in Italy.

SOLAR RADIATION

Solar radiation is electromagnetic energy which propagates in the space at light speed. It is concentrated in the range of lower wavelengths ($0.2\mu m \leq \lambda \leq 3\mu m$) with the maximum irradiance at 0.5 μm. The annual average radiation outside the terrestrial atmosphere is estimated about 1376 W/m^2. The annual average radiation that reaches the Earth surface is considered equal about to 1000 W/m^2: this value refers to a collecting surface perpendicular to the sun, in clear sky conditions and the sun at the zenith. However the exact amount in a given place is sensitive to atmospheric composition and to solar rays path: these factors affect diffusion and absorption phenomena that occurs in the atmosphere. Analyzing solar radiation that reaches the Earth surface, it is necessary to distinguish its components, which are sketched in Fig. 1. Let us consider a surface placed on the Earth which receives solar radiation. The radiation received directly from the sun is called direct radiation. The amount of scattered radiation coming from all the directions is called diffuse radiation. The ratio of radiation which reaches the surface after being reflected from the ground is called albedo. The sum of all the components incident on the surface is called total radiation.

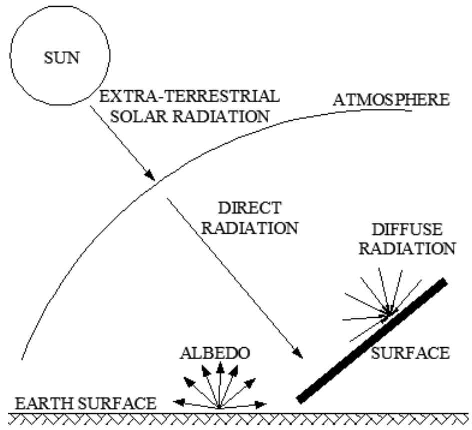

Figure 1. Solar radiation scheme.

THE SOLAR EXERGY ON THE EARTH

According to the first and second laws of thermodynamics, energy can not be created or destroyed. However, a process can diminish the capacity of energy to perform work due to the generation of entropy by irreversibility. In order to take into account this latter feature, exergy has been defined. Exergy represents the maximum work that can be extracted from a system in a given environment, that is carrying the system to its dead state. The dead state is the condition in which the system is in mutual equilibrium with the environment and so no more work can be extracted from it.

In order to determine the solar radiation exergy on the Earth, let us consider a cyclic machine placed on the terrestrial surface, as represented in Fig. 2. The machine extracts the maximum work $W_{\max}$ obtainable from the energy source E_s (solar energy) and it delivers heat Q_0 to the environment at temperature T_0. The machine also emits the energy by radiation E_e. The maximum work $W_{\max} = Ex_s$ is the exergy of the solar energy E_s. This scheme is quite general and it permits to obtain all the three most famous expressions for the solar exergy. In the scheme energies and entropies are per unit of time (indicated by a dot over the respective symbol) and per unit of area of the device represented by the cyclic machine: then the equations of balance involve specific fluxes of energy and of entropy.

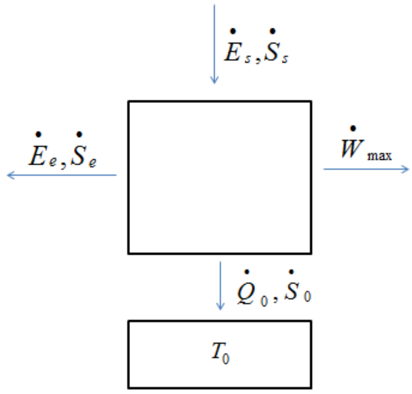

Figure 2. The cyclic machine.

Without emission by radiation from the cyclic machine

In this case the energy balance $\dot{E}_s - \dot{E}x_s - \dot{Q}_0 = 0$ and the entropy balance $\dot{S}_s - (\dot{Q}_0/T_0) = 0$ lead to the expression for the specific exergy flux

$$\dot{E}x_s = \dot{E}_s - T_0\dot{S}_s \tag{1}$$

Solar energy is transferred by heat interaction If it is considered that the solar energy is transferred by a heat interaction at sun temperature T_s, $\dot{S}_s = \dot{E}_s/T_s$ and it is obtained the specific exergy flux

$$\dot{E}x_s = \dot{E}_s(1 - \frac{T_0}{T_s}) \tag{2}$$

and the efficiency

$$\eta_J = \frac{\dot{E}x_s}{\dot{E}_s} = 1 - \frac{T_0}{T_s} \tag{3}$$

This efficiency is always positive and lesser than the unity as long as $T_0 < T_s$. This formula was proposed by Jeter [2]. Zamfirescu [3] adopted Eq. (3) but he introduced a lower temperature of the radiation on the terrestrial surface, in order to take into account the atmospheric filter.

Solar energy is a radiation flux If the source is radiation, some particularities should be taken into account: these regard the difference between black-body radiation and diluted black body radiation, more precisely the entropy transported by the two kinds of radiation.

It is known that a black-body radiation flux transports the specific energy flux

$$\dot{E} = \sigma T_s^4 \tag{4}$$

and the specific entropy flux

$$\dot{S} = \frac{4}{3}\sigma T_s^3 \tag{5}$$

where σ represents the Stefan-Boltzman constant, as reported for example in [4, 5].

Therefore, if the source is black-body radiation, specific energy and exergy fluxes are represented by Eq. (4) and Eq. (5) and the specific exergy flux of Eq. (1) become

$$\dot{E}x_s = \dot{E}_s\left(1 - \frac{4}{3}\frac{T_0}{T_s}\right) = \sigma T_s^4\left(1 - \frac{4}{3}\frac{T_0}{T_s}\right) \tag{6}$$

whereas the efficiency obtained is

$$\eta_S = \frac{\dot{E}x_s}{\dot{E}_s} = 1 - \frac{4}{3}\frac{T_0}{T_s} \tag{7}$$

This formula was determined by Spanner [6].

Pons [7] used the expression Eq. (1) for computing the specific exergy flux of the solar radiation, but he used for $\dot{E}_s$ and $\dot{S}_s$ the values measured on the Earth in some locations.

With emission by radiation from the cyclic machine

In this case the energy balance $\dot{E}_s - \dot{E}x_s - \dot{Q}_0 - \dot{E}_e = 0$ and the entropy balance $\dot{S}_s - (\dot{Q}_0/T_0) - \dot{S}_e = 0$ lead to the expression for the specific exergy flux

$$\dot{E}x_s = (\dot{E}_s - T_0\dot{S}_s) - (\dot{E}_e - T_0\dot{S}_e) \tag{8}$$

If the machine is considered a black-body at the same temperature of the environment T_0 , the second term in Eq. (8) becomes

$$(\dot{E}_e - T_0\dot{S}_e) = -\frac{1}{3}\sigma T_0^4 \tag{9}$$

Solar energy is a radiation flux If the solar energy is a black-body radiation flux at temperature T_s, the specific energy and entropy fluxes are represented by Eq. (4) and Eq. (5) and the specific exergy flux of Eq. (8) become

$$\dot{E}x_s = \sigma T_s^4\left(1 - \frac{4}{3}\frac{T_0}{T_s} + \frac{1}{3}\frac{T_0^4}{T_s^4}\right) \tag{10}$$

whereas the efficiency obtained is

$$\eta_P = \frac{\dot{E}x_s}{\dot{E}_s} = 1 - \frac{4}{3}\frac{T_0}{T_s} + \frac{1}{3}\frac{T_0^4}{T_s^4} \tag{11}$$

This formula was proposed by Petela [8].

Eq. (3), Eq. (7) and Eq. (11) were far discussed by various authors over the years, included Bejan [9] and Petela [5].

THE SOLAR ENERGY: FROM THE SUN TO THE EARTH SURFACE

Solar radiation undergoes to dissipation phenomena passing through the atmosphere: terrestrial solar radiation has lower irradiance than the extraterrestrial one.

The DBR model

Landsberg and Tonge [10, 11] took into account the losses suffered by radiation in the atmosphere by means of the DBR (diluted black-body radiation) model: they introducted a dilution factor ε, ranging between 0 and 1, independent of both the direction and the wavelength. If the sun is considered a diluted black-body, the specific energy and entropy fluxes are

$$\dot{E}_s = \varepsilon\sigma(T_s)^4 \tag{12}$$

$$\dot{S}_s = \chi\frac{4}{3}\varepsilon\sigma(T_s)^3 \tag{13}$$

where the χ function is

$$\chi = \frac{45}{4\pi^4}\frac{1}{\xi}\int_0^\infty y^2[(1+n_\nu)\ln(1+n_\nu) - n_\nu\ln(n_\nu)]dy \tag{14}$$

where $y = (\nu h)/(kT_s)$ represents a dimensionless frequency and n_ν is the mean occupation number of frequency ν.

For a more detailed analysis, it would be necessary to take into account the radiation spectral distribution of the radiation on the Earth surface, because the atmospheric absorption is not equal on all frequencies. Chu and Liu [12] investigated on the difference between extraterrestrial and terrestrial solar radiation and on the difference between direct and diffuse solar radiation: they do not used measured data, but a model for the spectrum of the solar energy on the Earth surface.

Exergy of diffuse and direct beam according to Pons

As already mentioned in the introduction, the passage of solar radiation through the atmosphere involves the splitting of solar radiation into direct and diffuse beams. Since these two components are subjected to different processes, in a deeper analysis it is not possible to unify them into a single entity.

Pons [7] treated the two components separately using representation illustrated by Eq. (6) and applying the correction factor χ proposed by Landsberg and Tongue [10, 11] to the direct and to the diffuse component separately. He analyzed real data of direct $\dot{E}_{dr}$ and diffuse $\dot{E}_{df}$ specific fluxes of solar radiation relative to Saint-Pierre de la Reunion, Odeillo and Ouagadougou. In Odeillo data was measured with a time step of 1 second and averaged over 5 minutes, in Saint Pierre de la Reunion data was measured with a time step of 6 seconds and averaged over 5 minutes, while data for Ouagadougou was calculated every hour by means of a software. The data was measured on a horizontal surface, and thus only the vertical component of direct radiation was determined. For computing the ε factor, it is necessary to divide the overall direct radiation on the Earth surface (not only the vertical component) by the extraterrestrial radiation. To calculate the direct radiation from its vertical component, the measured value $\mathrm{E_{dr}}$ was devided by the $\cos\theta$. θ is the angle between direct radiation and vertical direction and it depends on the latitude of the considered location and on the time. The atmospheric attenuation factor for direct and diffuse radiation was determined as follows

$$\varepsilon_{dr} = \frac{\dot{E}_{dr}/[\cos\theta\omega_s]}{\sigma T_s^4/\pi} \tag{15}$$

$$\varepsilon_{df} = \frac{\dot{E}_{df}/\pi}{\sigma T_s^4/\pi} \tag{16}$$

where ω_s is the Sun solid angle, that is the solid angle occupied by the direct radiation, while diffuse radiation occupies a solid angle equal to 2π. Regarding the χ functions for the diffuse and the direct radiation, Pons proposed the following functions

$$\chi_{dr}(\varepsilon_{dr}) = (0.973 - 0.275\ln\varepsilon_{dr} + 0.0273\,\varepsilon_{dr}) \tag{17}$$

$$\chi_{df}(\varepsilon_{df}) = (0.9659 - 0.2776\ln\varepsilon_{df}) \tag{18}$$

Then, the specific entropy fluxes $\dot{S}_{dr}$ and $\dot{S}_{df}$ were determined as follows

$$\dot{S}_{dr} = \chi_{dr}\frac{4}{3}\frac{\dot{E}_{dr}}{T_s} \tag{19}$$

$$\dot{S}_{df} = \chi_{df}\frac{4}{3}\frac{\dot{E}_{df}}{T_s} \tag{20}$$

The specific exergy flux was determined applying Eq. (1) for the two components

$$\dot{E}x_{dr} = \dot{E}_{dr} - T_0\dot{S}_{dr} \tag{21}$$

$$\dot{E}x_{df} = \dot{E}_{df} - T_0\dot{S}_{df} \tag{22}$$

where T_0 is the yearly air temperature average. The author [13] stated that for exergy computing T_0 has to be taken constant, in order to guarantee that exergy can be conserved in a reversible process. These formulas were integrated over a periodic time equal to the day (from sunrise to sunset). As the solid angles of direct and diffuse radiation are complementary, the total specific exergy flux was calculated as $Ex_S = Ex_{dr} + Ex_{df}$

SOLAR EXERGY FROM REAL SOLAR DATA ON THE ITALIAN AREA

Referring to the cyclic machine in Fig. (2), it could represent any sort of device that performs some useful effect by means of solar radiation. The aim of this work is the evaluation of the exergy of the solar radiation on the Italian area: this value should represent the maximum obtainable work and it should not be dependent on the device.

The device surface can absorb only a fraction of the short wave-length radiation coming from the sun, depending on its emissivity. Moreover, it can emit long wave-length radiation, because its temperature is rather close to the environmental one. The surface temperature and its emissivity are unknown and some authors supposed that it behaves like a black-body at environmental temperature T_0. For example, this hypothesis permits to obtain Eq. (10) and Eq. (11).

Since emissivity could assume different values on varying of the wave-length of the radiation, we imagine an ideal surface which absorbs all the solar radiation $\dot{E}_s$ and which does not emit radiation $\dot{E}_e$. In this way it is possible to determine the

Figure 3. Italian location analyzed : AG, AL, AN, AO, AP, AQ, BA, BL, BN, BO, BR, BZ, CA, CB, CL, CO, CS, CZ, EN, FE, FG, FI, FO, FR, GR, GE, GO, LI, MC, ME, MI, MN, NA, OR, PE, PG, PR, PT, PZ, RI, RM, RN, SO, SP, TA, TO, TN, TP, TR, VA, VE, VI

exergy of the solar radiation independently from the device surface. The characteristics of the device surface should be taken into account in a subsequent step.

Then, we have utilized the expression for the specific exergy flux of Eq. (1). For the calculation of $\dot{E}_s$ and $\dot{S}_s$, we have followed the approach proposed by Pons [7]: the direct and the diffuse components have been considered separately by means of the DBR model of Landsberg and Tonge [10, 11], and the χ_{dr} and χ_{df} functions have been calculated respectively by means of Eq. (17) and Eq. (18).

For the solar energy $\dot{E}_s$, we have started from the data reported in the UNI EN 10349 standard [14]. The standard [14] reports the monthly day average air temperature, the monthly daily average of specific direct and diffuse solar radiation on a horizontal surface E_{drh} and E_{df}, for all the Italian provincial capitals. We have chosen a subgroup of location shown in Fig. 3, in order to cover all ranges of latitude, longitude and altitude relative to Italy.

Data reported in the standard [14] are the average of ten years of measurements: the influence of any daily weather condition (for example cloudy sky) was spread on a large number of measurements.

In order to apply the approach proposed by Pons [7] we needed to spread the daily average monthly specific radiation during the day. The diffuse radiation can be considered constant during the day, but this is not possible for the direct radiation on a horizontal surface. Therefore we have represented the specific direct radiation on a horizontal surface by means of a sine funcion, whose area below is equal to the daily average monthly direct radiation. The sine function is the following

$$\dot{E}_{drh} = \left(\frac{\pi}{2}\frac{E_{drh}}{h_s}\right)\sin\left(\mathrm{t}\frac{\pi}{\mathrm{h_s}}\right) \tag{23}$$

where h_s represents the monthly average of the daylight duration in the considered location and t is the time interval from sunrise up to the instant considered. We have determined the specific direct radiation flux on horizontal surface every hour.

In order to calculate the dilution factors, we have determined the specific direct radiation that reaches the Earth every hour considering the angle θ between the direct radiation and the vertical direction. For computing the angle θ, first we have calculated the solar declination δ for each month

$$\delta = 0.40928\sin\left[2\pi\left(\frac{284+\mathrm{n}}{365}\right)\right] \tag{24}$$

where n is the number of the considered day. δ is the angle between incident radiation and the equatorial plane at noon on the considered meridian. Then we have calculated the hour angle h, which is the angular distance between the sun and its position at noon, along its apparent trajectory: h is zero at noon and varies of $\pi/12$ per hour (positive values in the morning hours and negative in the afternoon hours). The angle α between direct radiation and the horizontal surface, that is the complementary to θ angle, has been calculated as follows

$$\sin\alpha = \sin\mathrm{L}\sin\delta + \cos\mathrm{L}\cos\delta\cos\mathrm{h} \tag{25}$$

where L is the latitude of the given location. The angle α has been calculated for each time instant and for each month. Direct radiation $\dot{E}_{dr}$, that is the radiation that would be captured by a sun tracking device, has been calculated as follows

$$\dot{E}_{dr} = \frac{\dot{E}_{drh}}{\cos(\pi/2-\alpha)} \tag{26}$$

Solar radiation reaches the Earth surface only for a certain number of hours per day depending on the location and on the day. We have calculated daylight length average h_s for each month. The dawn time h_a and the sunset time h_t were calculated as follows:

$$h_a = -h_t = \mathrm{acos}(-\tan\mathrm{L}\tan\delta) \tag{27}$$

and the difference between h_a and h_t represents the daylight length h_s. From the monthly average air temperatures reported in [14], we have calculated the yearly average air temperature T_0. For each location, we have considered the same temperature in order to obtain comparable exergies.

As done by Pons [7], we have assumed the sun temperature T_s equal to 5770 K, the sun solid angle ω_s equal to 6.79 10^{-5} sr and we have applied Eq. (15) - Eq. (22).

We have calculated the exergy factors of direct and diffuse solar radiation

$$\eta_{dr} = \frac{Ex_{dr}}{E_{drh}} \tag{28}$$

$$\eta_{df} = \frac{Ex_{df}}{E_{df}} \tag{29}$$

η_{dr} represents the ratio of the exergy of the direct radiation and the vertical component of the direct radiation. η_{df} represents the ratio of the exergy of the diffuse radiation and the diffuse radiation. As can be seen in Fig. 4 and Fig. 5, η_{dr} ranges

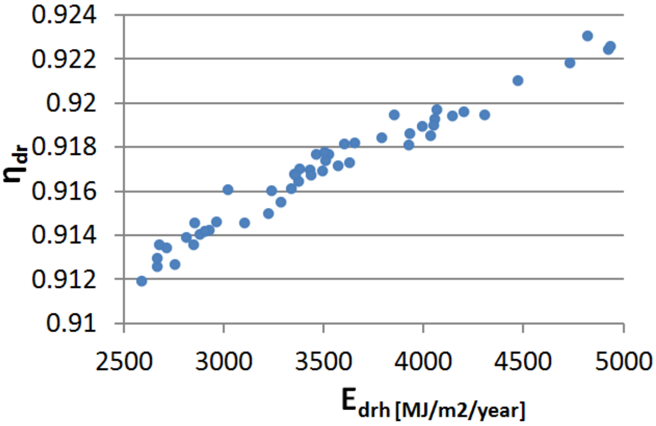

Figure 4. Exergy factor of direct solar radiation

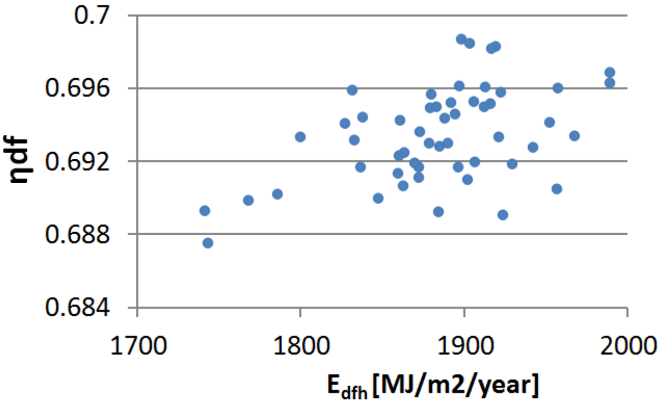

Figure 5. Exergy factor of diffuse solar radiation

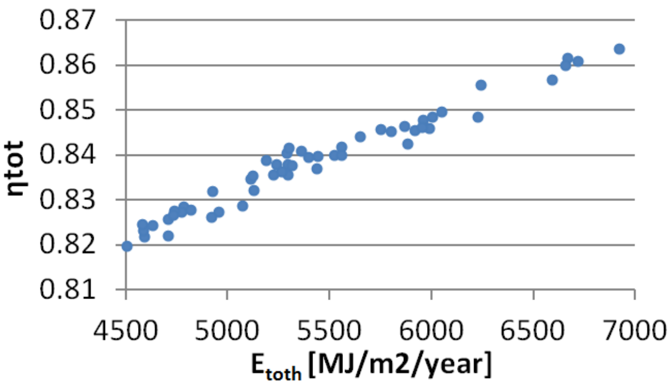

Figure 6. Exergy factor of total solar radiation

between 0.912 and 0.923, while η_{df} ranges between 0.688 and 0.699. We have calculated the total exergy factor for each considered location as follows

$$\eta_{tot} = \frac{Ex_{tot}}{E_{toth}} \tag{30}$$

where $Ex_{tot} = Ex_{dr} + Ex_{df}$ is the yearly solar radiation exergy and $E_{toth} = E_{drh} + E_{df}$ is the yearly solar radiation that reaches an horizontal surface. In Fig. 6, η_{tot} is shown and it ranges between 0.820 and 0.864.

Fig. 7 shows the trend of total exergy factor as a function of altitude (without distinction for latitude). The more the altitude, the lower the thickness of the atmospheric layer that solar radiation has to pass through for reaching the Earth surface (latitude

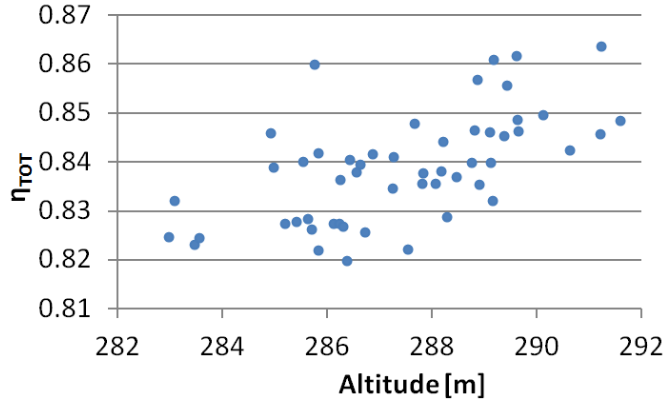

Figure 7. Total exergy factor as function of altitude

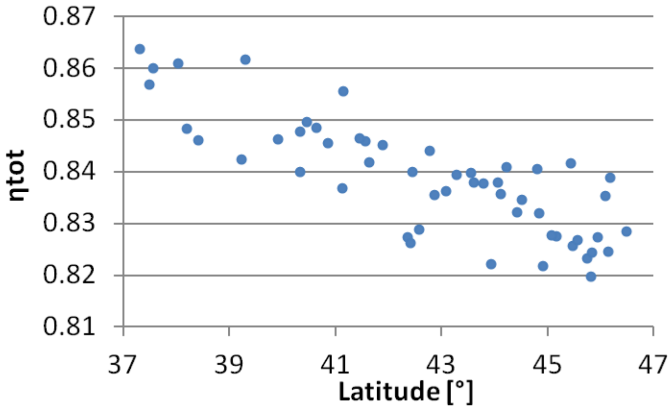

Figure 8. Total exergy factor as function of latitude

being equal). In Fig. 7 there is no any identifiable trend: latitude does not affect the exergy factor predominantly.

Fig. 8 shows the trend of total exergy as function of latitude. Increasing latitude increases the thickness of the atmospheric layer that solar radiation has to pass through for reaching the Earth surface. It is noted that with increasing latitude, the total exergy factor decreases.

The exergy calculation involves the environment temperature T_0 as shown in Eq. (1) and, if the latitude incrases, the average annual temperature T_0 decreases: for example, in Messina (latitude 38°11') T_0 is equal to 291.55 K, while in Belluno (latitude 46°08') T_0 is equal to 282.96 K. Fig. 9 shows the total exergy factor as function of the yearly air temperature average. Increasing T_0, total exergy factor increases. This is probably due to the fact that in locations with high temperature the radiation is stronger. This indicates that solar radiation exergy is more affected by the quantity of solar radiation than by the environment temperature.

Fig. 10 shows that increasing the ratio between direct and diffuse solar radiation, the total exergy factors increases.

We have also applied our procedure on the three location analyzed by Pons [7] (Ouagadougou, Odeillo and Saint Pierre de la Reunion), using direct and diffuse solar radiations on horizontal surface calculated by means of a software. We have calculated the ratio Ex_{dr}/E_{toth} and $\eta_{tot} = Ex_{tot}/E_{toth}$: Tab. 1 shows that we have found different, but comparable data.

It is also interesting to see the trend of the total exergy factor as function of the ratio of specific vertical direct radiation and specific diffuse radiation. In Fig. 10 it can be noted that increas-

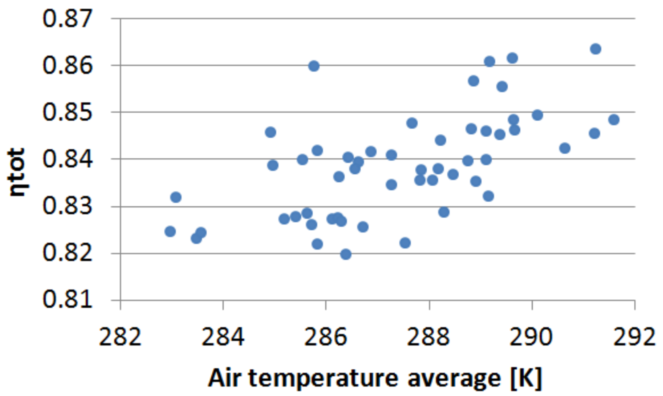

Figure 9. Total exergy factor as function of yearly air temperature average

Table 1. Total exergy factor: comparison between data calculated by Pons and data that we calculated

	Location	Pons	Our computing
Ex_drh/E_toth	St Pierre Reunion	0.63	0.67
	Ouagadougou	0.58	0.66
	Odeillo	0.62	0.56
Ex_tot/E_toth	St Pierre Reunion	0.86	0.86
	Ouagadougou	0.84	0.84
	Odeillo	0.85	0.83

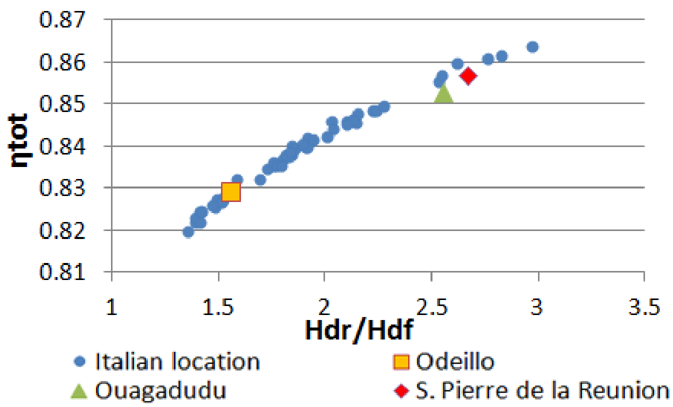

Figure 10. Total exergy factors as function of the ratio between direct and diffuse radiation

ing the percentage of this ratio the total exergy factor increases. This trend is also followed by the three locations analyzed by Pons [7].

At the end, as η_{tot} values are very similar for all the Italian locations, it was decided to determine a single value η_{IT} valid for Italy, by means of which to determine the solar radiation exergy. This factor has been determined as average of the values obtained for the analyzed locations and it is

$$\eta_{IT} = 0.839 \tag{31}$$

In this way, it is possible to calculate solar radiation exergy multiplying this factor for the total solar radiation measured in an Italian location.

CONCLUSIONS

The aim of this work has been the evaluation of the exergy of the solar radiation on the Italian area: this value should represent the maximum obtainable work and it should not be dependent on the characteristics of the device surface. Then we have imagined an ideal surface which absorbs all the solar radiation $\dot{E}_s$ and which does not emit radiation $\dot{E}_e$. Following the analysis proposed by Pons, we have analyzed real radiation data and we have treated direct and diffuse radiation separately. We have proposed a single exergy factor valid on the Italian area, which is to be applied to the total radiation measured on horizontal surface.

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