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A universal model for solar radiation exergy accounting: Case study of Tunisia

KHAOULA DAGHSEN[a,b]
DORRA LOUNISSI[b*]
NAHLA BOUAZIZ[b]

[a] University of Monastir, National Engineering School of Monastir,
Rue Ibn El Jazzar, Monastir 5000,
Rue Ibn Jazzar, Monastir 5035, Tunisia

[b] University of Tunis El Manar, National Engineering school of Tunis,
Energy and Environment Laboratory LR21ES09,
ENIT. BP 37, Le Belvedere 1002

Abstract The global solar radiation is the origin for all environmental processes on the earth and the majority of energy sources are derived from it. The data of solar radiation are required for the design and the study of solar application systems. The more important is the quality of the solar radiation which is defined by the maximum work can be provided by the solar radiation. This quality is measured by the exergy content of a solar radiation. In the present work, a universal pattern has been built to provide a prediction of solar exergy dependently to the geographic location. Fitting models have been developed for exergy account depending on geographic location, based on the linear, quadratic, cubic, logarithmic, exponential, power regression. The Petela model is adopted from literature for exergetic efficiency accounting of solar radiation. The global solar radiation according to ASHRAE model is expressed dependently of the cosine of zenith angle. The developed model is applied on Tunisia regions to predict exergy solar potential. The studied regions are classified regarding the exergy account, high, medium and low solar exergy locations. Results show that generally the solar radiation shows a low degree of exergy content, about 7% of difference.

Keywords: Solar energy; Radiation; Exergy radiation; Exergy potential; Regression

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*Corresponding Author. Email: dorra.lounissi@gmail.com

Nomenclature

A, B, C – empirical coefficients for solar irradiance calculations according to ASHRAE model, W/m^2
CEL – cumulative exergy loss, kWh
D – diffuse solar radiation on the horizontal surface on a clear day, W/m^2
Dp – depletion number
E_{rad} – energy of radiation, kWh/m^2
Ex_{rad} – exergy of radiation, kWh/m^2
ESI – exergy sustainability index
G – global solar radiation, W/m^2
G_{ex} – global solar radiation exergy, W/m^2
I_n – beam solar radiation in the direction of rays, W/m^2
MAPE – mean absolute percentage error
R^2 – correlation coefficient
T_{Sun} – sun temperature, K
T_0 – environment temperature, K
W – work performed by a system, kWh/m^2
y_c – calculated values
y_p – predicted values
$y_{c,\text{avg}}$ – average of the calculated values
$y_{p,\text{avg}}$ – average of the predicted values

Greek symbols

η – energy efficiency
Ψ – exergy efficiency
θ_z – zenith angle, deg
φ – latitude of a given position, deg
δ – solar declination, deg
ω – hour angle, deg

1 Introduction

The use of renewable energy is the key to satisfy the growing energy demand, to decarbonize the world economy and to reduce the global climate change [1,2]. A renewable energy comes from sources that nature constantly renews, as opposed to non-renewable energy whose stocks are running out. The use of renewable energies or as so-called ‘green energies’ generates very little waste and polluting emissions. So, they do not damage the environment [3]. Solar energy has the highest energy level among all renewable sources. And many sources of energy are derived from it, in particular: hydraulic energy, wind energy, tidal power and wave energy, wood energy and biomass energy as well as very low temperature geothermal energy. Fossil fuels could be added, coming from organic matter created by photosynthesis (coal, petroleum, natural gas, etc.) to which is added the biochemical energy of living organic matter [4]. Currently, there are two main ways for using solar energy; the solar photovoltaic, which converts solar radiation directly into electricity and solar thermal energy which converts radiation directly into heat. The concentrated solar power is a thermal solar energy. This technology uses the heat from the sun radiation in order to subsequently transform it into electricity. Many research programs are underway to design solar technologies and to improve their efficiency. Solar energy data are essential to perform these studies especially solar radiation which have been carried out by many researchers over many years [5–9]. Currently, governments and energy deciders are not interested to the conversion of the solar energy into high-quality energy (mechanical and electrical energies). However, this conversion plays a crucial role in the solar technology efficiency and the environment respect. Unlike the energy concept which is aimed at the quantity, the exergy is measure of the energy quality. It is defined as maximum work that can be provided from a system at a specific state and when it comes to equilibrium [10, 11]. It is the fraction of the energy that is convertible into high-quality energy; mechanical or electrical energy. While energy is based on the first law of the thermodynamic (the conservation of the energy in processes and transformation), the exergy is based on the second law of thermodynamic that announces the creation of the entropy which measures the irreversibility associated with the process. So based on this law, energy is not constant during a process; and is degraded. The concept of the exergy includes the consumption or the degradation aspects of the useful energy to an unwanted form in the course of a transformation. Based on this background; the calculation of the solar exergy is important for analyzing the quality of the incoming solar energy and for designing solar energy system. Different researches had been carried out to predict the solar radiation exergy. Ziębik [12] have analysed the fundamental trends in the Polish energy policy based on the first and second law of thermodynamics, he have carried out a thermodynamical analysis of the ratio of final and primary energy. Chu and Liu [13] have computed the exergy of the extra-terrestrial and the terrestrial solar radiation based on the definition of radiative exergy of Candau [14] and they have compared their result by using the solar spectral radiation databank developed by Gueymard [15]. Kabelac has shown how the radiation entropy flux arriving on earth is to be calculated and he has found that 50–77% of the incoming radiation energy is convertible into useful energy; or the exergy content in the solar radiation [16]. Joshi, Dincer and Reddy [17] have developed a solar exergy map concept and have evaluated the performance of a photovoltaic thermal system for different Indian cities, for a year and for different cities of USA for different months. Alta *et al.* [18] have mapped the national spatial distribution of mean monthly exergy values of solar radiation over Turkey based on solar radiation data from 152 georeferenced locations. Jiménez-Munoz *et al.* [19] have analysed recent trends in solar exergy and net radiation at global scale during the period 1980–2010, distinguishing between land and ocean and between different land cover classes. Hepbasli and Alsuhaibani conducted a study to review various solar exergy models used in solar energy-related applications and to estimate the solar exergetic values for some regions of Saudi Arabia and Turkey [20]. Uçkan has analysed the solar radiation exergy for the period of 1993 to 2007 in Van in Turkey based on meteorological data and using various models [21]: Petela model [22], Spanner model [23], and Jeter model [24]. Arslanoglu has developed three different empirical models linear, quadratic and cubic in order to predict the monthly average daily global solar radiation exergy on a horizontal surface in different regions of Turkey based on meteorological data [25]. Jamil and Bellos have estimated the exergy of incoming solar radiation using empirical models based long-term meteorological data (1986-2000) for 23 selected stations in India [26]. Khorasanizadeh have calculated the monthly average daily solar radiation exergy on a horizontal surface for eight capital provinces of Iran using five empirical models with linear, quadratic, cubic, exponential and power functional forms [27].

In this study, a universal model is built to predict the solar radiation exergy dependently of the zenith angle for all regions in the earth. An application to Tunisia highlights the distribution of the exergy solar radiation in its different regions. It is shown that Tunisia has a high potential of solar radiation with 41% annual solar insolation. Nevertheless, there is no research that has been carried out to date on status of solar exergy in this country.

2 Solar exergy and solar energy technology

Energy is conserved and cannot be generated or destroyed. The energy balance equation for a non-steady flow process is as follows:

$$\text{Energy Stored} = \text{Energy Input} - \text{Energy Output}. \tag{1}$$

The exergy balance equation for a non-steady flow process can be written as

$$\begin{aligned}\text{Energy Stored} = \text{Energy Input} - \text{Energy Output}\\ - \text{Exergy Consumption}.\end{aligned} \tag{2}$$

When comparing Eqs. (1) and (2), it is evident that the extra term of exergy consumption in Eq. (2) refers to the irreversibility in the system. Energy efficiency is the ratio of energy in product and total energy input

$$\eta = \frac{\text{Energy Output}}{\text{Energy Input}}\,, \tag{3}$$

while exergy efficiency is the ratio of exergy in product and total exergy input [28]

$$\Psi = \frac{\text{Exergy Output}}{\text{Exergy Input}}\,. \tag{4}$$

According to Eq. (2), when the irreversibility of a system grows, the exergy output decreases while the exergy input remains constant, lowering the system's exergy efficiency. This effect of system irreversibility is not seen in energy analysis; hence it is incapable of determining the true losses associated with a process. Exergy analysis can identify the magnitude of thermodynamic losses and processes that are responsible for them. Therefore, exergy efficiency is the measure of the approach to true ideality. It gives a realistic view of the system. The exergy entails an important relationship with the surrounding environment and, given its origins in the second law of thermodynamics, it moves towards the realm of irreversible processes, which are those that actually take place in reality, in societies [29, 30]. The ability to locate inefficiencies within energy systems and compare technologies on a level playing field makes exergy analysis the appropriate analysis technique for technical decision making [29]. As Sciubba points out, exergy efficiency has a profound impact on the design of energy conversion systems, up to the point that almost every design standard today makes either a direct or indirect use of exergy when searching for an optimal configuration [31]. In evaluating the performance of solar energy systems using exergy analysis method, calculation of the exergy of radiation is very crucial. A new integration of solar still with photovoltaic module (PV) is performed based on exergy, exergoeconomic, and exergoenvironmental assessment [32]. This new integration is based on installing the PV module over the back side of the solar still while its output electrical power is converted directly to thermal heat to heat the saline water in the basin [32]. Luminosu and Fara have determined the optimal operation mode of a flat solar collector by exergetic analysis [33]. The method has proven valuable in the design of solar collectors for the specific climatic and insulation conditions of a certain region. The design and the analysis for sustainable energy systems have been performed by Sala-Lizarraga *et al.* [34] by applying the concept of cost (an economic concept) to exergy, as exergy combines the quantity of energy with its quality factor. Harish and Piyush [35] have reviewed the works related to energy and exergy analysis of various types of solar air heaters, their work aimed to find out the research gap for future work. For efficient utilization of solar energy, the exergy analysis is used for optimal design of solar air heaters. Harish [36] has developed the energy and exergy analysis for roughened solar air heater using arc shaped wire ribs for performance improvement. Sobhnamayan *et al.* [37] have carried out the optimization of a solar photovoltaic thermal water collector which is based on exergy concept.

Table 1 shows exergy efficiencies for several solar energy systems. As can be seen the solar exergy is considered as the input load to these systems. As a result, the exergy content of a solar radiation affects directly the selection of the convenient solar technology and it can be employed by solar energy planners and researchers to introduce appropriate policies for energy conservation and management.

Table 1: Exergy efficiencies for several solar energy systems.

Solar system	Exergy efficiency	Significance	References
Domestic-scale solar water heater	$\Psi_{s,\text{heater}} = \dfrac{Ex_{\text{heat}}}{Ex_{\text{Sun}}}$	Ex_{heat}: the exergy from the water storage barrel to the end-user Ex_{Sun}: the exergy of the solar radiation	[44]
Solar collector	$\Psi_{s,\text{col}} = \dfrac{Ex_{\text{cool, tank}}}{Ex_{\text{Sun}}}$	$Ex_{\text{col, tank}}$: the exergy from the collector to the storage barrel Ex_{Sun}: the exergy of the solar radiation	[44]
PV system	$\Psi_{s,\text{col}} = \dfrac{Ex_{\text{output}}}{Ex_{\text{Sun}}}$	Ex_{output}: the exergy gained by the solar PV Ex_{input}: the exergy of the solar radiation	[45]
Hybrid photovoltaic thermal system	$\Psi_{\text{PV/T}} = \dfrac{Ex_{x_{\text{e}}} + Ex_{\text{th}}}{Ex_{\text{Sun}}}$	Ex_e: the electrical exergy produced by the PV panels Ex_{th}: the thermal exergy available on the photovoltaic (PV) panel Ex_{Sun}: the exergy from the solar radiation	[17, 45]

Reducing exergy losses is tantamount to reducing resource consumption and to reducing environmental pollution and its consequences [11,38]. Recognizing exergy losses in processes and implementing necessary policy changes can help a society become more sustainable in the future. The sectoral exergy analysis is applied by a lot of researchers to evaluate a performance of a sector by determining the locations and amount of exergy loss by tracking the energy flow of each end use. It is an exploring tool for sustainable energy policies and adaptation strategies for the sector [39]. The consideration of the exergy instead of the energy in system design and in energy quantification will lead to a sustainable use of energy resources. For example, Rosen and Dincer proved in a recent study that the increase of sustainability and the decrease of environmental impact as the process exergy efficiency increases [11]. They pointed out that when exergy efficiency approaches 100%, environmental impact approaches zero, since exergy is only converted from one form to another without loss, either through internal consumptions or waste emissions. Also, sustainability approaches infinity because the process approaches reversibility. They also demonstrated that as exergy efficiency approaches 0%, sustainability approaches zero since exergy-containing resources are used but no work is accomplished. Furthermore, the environmental impact approaches infinity since, in order to offer a fixed service, an ever-increasing quantity of resources must be employed, resulting in an ever-increasing amount of exergy-containing wastes being discharged. Cornelissen revealed that one important element in obtaining sustainable development is the use of exergy analysis [40]. The study suggests that exergy losses, particularly due to the use of non-renewable energy forms, should be minimized to obtain sustainable development. Furthermore, the study demonstrates that the environmental effects of emissions and resource depletion can be described in terms of a single exergy-based index based on physical principles. Sustainability is a key in solving current ecological, economic, and developmental problems [11]. Sustainability of the process or a system is ensured when resources are used efficiently. It can be improved by the exergy analysis. In this regard, several exergetic indicators that are used in order to track the sustainability have been applied for a lot of systems and sectors [39, 41]. The first indicator used is the depletion number (Dp). It is regarded as an essential parameter as it measures the effectiveness of fossil fuel utilization and has an inverse relationship with exergy efficiency. Fossil fuel depletion harms the environment and to ensure maximum sustainability the reference value of this indicator should be zero. That is, the higher the exergy efficiency of a system, the lower is the exergy destruction and depletion number. The depletion number can be written as [42]

$$\mathrm{Dp} = \frac{\text{Exergy Destroyed}}{\text{Exergy Input}}\,. \tag{5}$$

The exergy sustainability index (ESI) is inversely proportional to the depletion number [42]

$$\mathrm{ESI} = \frac{1}{\text{Depletion Number}}\,. \tag{6}$$

Exergy sustainability index is closely interconnected with sustainable development. The value of ESI typically ranges between 0 and infinity. Higher values of ESI include lower depletion of resources and lower environmental impact [38].

The cumulative exergy loss (CEL) indicates the amount of available energy that is lost in a process or sector and can be written as [43]

$$\mathrm{CEL} = \sum \text{Input Exergy} - \sum \text{Output Exergy}. \tag{7}$$

If cumulative exergy loss rises with time, it shows that the whole sector or process is consuming exergy and less exergy is available at the output. A higher CEL signifies lower sustainability.

Other exergetic indicators in literature could be evaluated to provide critical information in addressing the sustainability of any sector or system [32, 35]. These indicators enable the selection of the proper appliances and the effect of lost exergy on the environment. Policymakers of countries should implement exergy-based sustainability indicators in addressing the sustainability of different sectors.

3 Methodology

3.1 Solar exergy modeling

The calculation of the exergy flow of the incident solar radiation was investigated by a lot of researchers, such as Petela [22], Spanner [23], Press [46], Landsberg and Tonge [47], Parrott [48, 49], Jeter [24], Kabelac [50], Millan *et al.* [51], Wurfel [52], etc.

According to Petela, the energy and the exergy conversion efficiencies of thermal radiation are defined as follows. The real energy conversion efficiency (η_e) of thermal radiation into work can be defined as the ratio of the work (W), performed by a system due the use of the radiation, to the energy (E_{rad}) of this radiation:

$$\eta_e = \frac{W}{E_{\text{rad}}}\,. \tag{8}$$

The exergy conversion efficiency of thermal radiation into work can be defined as the ratio of the work (W), by a system due the use of the radiation, to the exergy (Ex_{rad}) of this radiation as

$$\eta_{\text{ex}} = \frac{W}{Ex_{\text{rad}}}. \tag{9}$$

In an ideal (reversible) process the maximum work ($W_{\max}$) can be obtained from radiation energy. Then, this work is the exergy of the radiation, $W_{\max} = Ex_{\text{rad}}$, and the efficiency ($\eta_e$) changes to the maximum conversion efficiency ($\eta_{e,\max}$) which is equal to a ratio Ψ the conversion of solar radiation into work:

$$\eta_{e,\max} = \psi = \frac{Ex_{\text{rad}}}{E_{\text{rad}}}\,. \tag{10}$$

The widely used models for characterizing the conversion of solar radiation into work (Ψ) are those of Petela [22], Spanner [23] and Jeter [24]. Petela modeled the exergy of thermal radiation by the use of cylinder-piston analogy containing the radiation of an isotropic black body at a temperature T and analyzing the mechanisms of absorption, emission and work production [22]. The adiabatic and reversible expansion process led to the following equation for the conversion efficiency of solar radiation into useful work:

$$\psi_{\text{Petela}} = 1 - \frac{4}{3}\frac{T_0}{T_{\text{Sun}}} + \frac{1}{3}\left(\frac{T_0}{T_{\text{Sun}}}\right)^4, \tag{11}$$

in which T_0 and T_{Sun} and are the environment temperature and the Sun temperature, respectively. The same expression has been independently derived by Landsberg and Tonge [47] and Press [46]. Spanner replaced Petela's reversible process with an irreversible spontaneous process and took into account the absolute work instead of useful work [23]. The efficiency of direct solar radiation is then expressed as follows:

$$\psi_{\text{Spanner}} = 1 - \frac{4}{3}\frac{T_0}{T_{\text{Sun}}}\,. \tag{12}$$

Jeter suggested the Carnot efficiency in analyzing the concepts of radiation and heat transfer during the expansion process, the conversion efficiency of solar radiation into useful work found by Jeter is as follows [24]:

$$\psi_{\text{Jeter}} = 1 - \frac{T_0}{T_{\text{Sun}}}\,. \tag{13}$$

As the conclusion of Jeter, Kabelac [50], and Millan *et al.* [51], considered the Carnot efficiency as the upper limit of the conversion of solar radiation to work. Bejan analysed the validity of these expressions and concluded that they are individually correct and complementary, but they depend on the definition associated with useful work and energy consumed [53]. Petela examined in detail the three formulas proposed by Petela, Spanner and Jeter, respectively, and he confirmed that Petela's formula is justified for the estimation of the exergy radiation existing at a certain instant regardless its origin and its variation in the next instant [54]. In this work, the Petela model is adopted for all exergy solar radiation considerations.

A large number of scholars have carried out relevant studies on global solar radiation and established corresponding estimation models, among which ASHRAE clear-sky global solar radiation model [55] has been widely used because of its simple equation structure, clear physical significance and convenient utility. ASHRAE model is proposed by the American Society of Heating, Refrigerating and Air-Conditioning Engineers for estimating the global solar radiation on a horizontal surface in clear day. As recommended by ASHRAE, global solar radiation (G), beam solar radiation in the direction of rays (I_n), and diffuse solar radiation (D) on the horizontal surface on a clear day are calculated using as the following equations, respectively [55]:

$$G = I_n \cos\theta_z + D. \tag{14}$$

The direct normal irradiance by this model is given as

$$I_n = A \exp\left(-B/\cos\theta_z\right). \tag{15}$$

The diffuse radiation flux is given by

$$D = C I_n. \tag{16}$$

The θ_z in those equations is the zenith angle and its cosine is given by the equation

$$\cos\theta_z = \sin(\varphi)\sin(\delta) + \cos(\varphi)\cos(\delta)\cos(\omega), \tag{17}$$

where φ, δ, and ω are the latitude of a given position, solar declination and hour angle, respectively. Values of A, B, and C are the empirical coefficients for solar irradiance calculations according to ASHRAE model and they are listed monthly in Table 2. The equation (14) of global solar radiation G can be rewritten as follows

$$G = \left[A \exp\left(\frac{-B}{\cos\theta_z}\right)\right](\cos\theta_z + C). \tag{18}$$

Table 2: The parameters of the ASHRAE model.

Month	Empirical coefficients		
	A (W/m^2)	B (–)	C (–)
March	1186	0.156	0.071
April	1136	0.18	0.097
May	1104	0.196	0.121
June	1088	0.205	0.134
July	1085	0.207	0.136
August	1107	0.201	0.122
September	1152	0.177	0.092
October	1193	0.16	0.073
November	1221	0.149	0.063
December	1234	0.142	0.057
January	1230	0.142	0.058
February	1215	0.144	0.06

3.2 Solar exergy predicting models

In order to develop a universal model for solar radiation exergy account which depends on the ambient temperature and the cosine of zenith angle, as seen in Eq. (18), the expression of the radiation G during the day and the Petela conversion efficiency of solar radiation are used according to Eqs. (18) and (11). The solar radiation exergy G_{ex} can be found for any required regions as follows:

$$G_{\text{ex}} = \psi\left(T_0\right)G\left(\cos\theta_z\right) = f\left(T_0\right)f\left(\cos\theta_z\right). \tag{19}$$

The exergy of solar radiation is given using formula

$$Ex_{\text{rad}} = \int \frac{1}{1000} G_{\text{ex}}(\cos\theta_z)\Delta t, \tag{20}$$

where the zenith angle (θ_z) depends on time and is determined by using the Solar Position Calculator [56], and Δt is the period time of energy calculation.

In order to establish the empirical model for predicting the solar exergy dependently on the geographic location, as expressed in Eq. (19), six relations; linear, quadratic, cubic, logarithmic, exponential and power were adopted in this study. The equations of these regression models are presented in Table 3.

Table 3: The regression models proposed in the literature that used in this study.

Models	Regression equations
Linear	$y = ax + b$
Quadratic	$y = ax^2 + x + c$
Cubic	$y = ax^3 + bx^2 + cx + d$
Power	$y = ax^b$
Exponential	$y = e^{ax+b}$
Logarithmic	$y = a \ln x + b$

To evaluate the performance of the calibrated models two statistical indicators of mean absolute percentage error (MAPE), correlation coefficient (R^2) have been utilized. Correlation coefficient expresses the linearity of the relationship between the calculated and predicted values and varies between –1 and +1. The values of 1 show the complete linearity of the relationship between the calculated and predicted values and the value of 0 indicates the absence of a linear relationship. This indicator is defined as follows [57]:

$$R^2 = \frac{\sum_{i=1}^{k} \left(y_p - y_{p,\mathrm{avg}}\right)\left(y_c - y_{c,\mathrm{avg}}\right)}{\sqrt{\left[\sum_{i=1}^{k} \left(y_p - y_{p,\mathrm{avg}}\right)^2\right]\left[\sum_{i=1}^{k} \left(y_c - y_{c,\mathrm{avg}}\right)^2\right]}}, \tag{21}$$

where y_p is the ith predicted value, y_c is the i-th calculated value, k is the total number of observations, and $y_{p,\mathrm{avg}}$ and $y_{c,\mathrm{avg}}$ are the averages of the predicted and calculated values, respectively.

Mean absolute percentage error represents the absolute average value of the percentage deviation between the predicted and the calculated values. The ideal value of the MAPE is zero. The MAPE is defined as [58]

$$\mathrm{MAPE} = \frac{1}{k} \sum_{i=1}^{k} \left(\left| \frac{y_p - y_c}{y_c} \right| \times 100 \right). \tag{22}$$

3.3 Data collection for regression

- To develop the universal model for exergy account: $\psi(T_0)$ is calculated for 170 different ambient temperatures and $G(\cos\theta_z)$ is calculated for $200 \cos\theta_z$. All the required data are taken from the Solar Position Calculator [56].

- As application to the developed model, Tunisia is considered as case study. It is located on the Mediterranean coast of Northwest Africa between $30° 13'$ and $37° 21'$ north latitude and $7° 30'$ and $11° 36'$ eastern longitude and it has an average elevation of about 235 m above the sea level. The data of energy measurement and ambient temperature used in the exergy study of solar radiation for the 24 Tunisian regions are taken from the National Institute of Meteorology of Tunisia and the data are taken for different months. The 24 studied regions are spanned all over Tunisia and they have different climatic conditions. In order to calculate their solar radiation exergy, the monthly average values of the outdoor temperature are considered as reference temperature T_0. The characteristics of the different locations; the latitude, longitude and elevation above the sea level are described in Table 4.

Table 4: Geographical parameters for the studied Tunisian locations.

Location	Latitude	Longitude	Altitude (m)	Location	Latitude	Longitude	Altitude (m)
Tunis	$36° 79'$	$10° 14'$	13	Beja	$36° 72'$	$9° 18'$	211
Bizerte	$37° 28'$	$9° 86'$	43	El kef	$36° 16'$	$8° 70'$	539
Gafsa	$34° 42'$	$8° 77'$	305	Zaghouan	$36° 40'$	$10° 13'$	197
Nabeul	$36° 45'$	$10° 71'$	22	Tatouine	$32° 92'$	$10° 44'$	276
Manouba	$36° 80'$	$10° 07'$	34	Jendouba	$36° 50'$	$8° 77'$	144
Ariana	$36° 86'$	$10° 17'$	77	Kebili	$33° 70'$	$8° 97'$	53
Gabes	$33° 88'$	$10° 10'$	7	Mahdia	$35° 50'$	$11° 05'$	3
Monastir	$35° 75'$	$10° 81'$	26	Benarous	$36° 74'$	$10° 23'$	22
Medenine	$33° 34'$	$10° 49'$	100	Tozeur	$33° 91'$	$8° 11'$	59
Sousse	$35° 82'$	$10° 61'$	30	Kasserine	$35° 17'$	$8° 82'$	662
Siliana	$36° 08'$	$9° 36'$	434	Sidi bouzid	$35° 03'$	$9° 47'$	339
Sfax	$34° 76'$	$10° 73'$	17	Kairouan	$35° 67'$	$10° 10'$	60

4 Results and discussion

The aim of this study is present a universal model for exergy solar radiation accounting. A case study of Tunisia is investigated. Petela model is used to represent exergy efficiency. ASHRAE model is adopted for solar energy radiation calculation.

4.1 Regression result of the solar radiation exergy universal model

For exergy account at any geographic location, fitting models have been developed based on the linear, quadratic, cubic, logarithmic, exponential, and power regression. First of all, the Petela ratio (ψ) is formulated as function of the ambient temperature. Then the global solar radiation (G) is written dependently of the cosine of zenith angle. Lastly, the best correlation of ψ and G are grouped. The correlation coefficients and the statistical indicators (MAPE and R^2) for the developed models are described in Table 5. The exponential model in terms of MAPE, provides the lowest error with 0.0048% and the best value of R^2 equal to 1.00. There for it presents the best model for ψ_p correlation. For the energy solar radiation G regression, the best result of R^2 and the MAPE is obtained with the cubic model with a values of consequently 0.9967 and 9.3414%. The universal expression for exergy account can be therefore written as follows:

$$G_{\mathrm{ex}} = \Big(26.6\cos^3\theta_z - 42.9\cos^2\theta_z + 1141.2\cos\theta_z - 66\Big) \times \exp\left(-0.0002 + 0.0018T_0\right), \tag{23}$$

where, θ_z is the zenith angle of the location and T_0 is the ambient temperature.

Table 5: The regression constants and the statistical indicators for the calibrated models for a universal solar radiation exergy account.

Parameter	Model	a	b	c	d	R^2	MAPE, %
$G = f(\cos\theta_z)$	Linear	1157.7753	−81.8427	–	–	0.9963	9.7830
	Quadratic	−42.9148	1157.7753	−66.0386	–	0.9966	9.7915
	Cubic	26.6014	−42.9148	1141.1815	−66.0386	0.9967	9.3414
$\Psi p = f(T_0)$	Linear	−0.0002	1.0000	–	–	1.0000	0.0051
	Power	1.3131	−0.0603	–	–	0.9924	0.0837
	Exponential	−0.0002	0.0018	–	–	1.0000	0.0048
	Logarithmic	−0.0568	1.2550	–	–	0.9932	0.0789

4.2 Case study of Tunisia results

The variation of the monthly average values of the solar radiation energy and exergy in the studied regions of Tunisia are represented in Fig. 1. Generally, the solar radiation shows a bass degree of exergy content about 7% in comparison with the energy content in the different locations. Thus, the exergy concept consists to provide the maximal useful work that can be produced from an energy flow.

From the figure it's observed that some locations represent a high value of solar exergy varying from 2100 kWh/m^2/year to 2270 kWh/m^2/year such as Gafsa, Gabes, Medenine, Tozeur, Kebili, and Tataouine. These regions are located near to each other, in the south of Tunisia. The regions located at the centre zone have lower exergy content than those of the southern regions. But a not expected result is observed in Fig. 1, in fact, the region of Kairouan have a low exergy content comparing to its neighbours regions. All the regions of the center have an exergy content varying from 1980 kWh/m^2/year to 2050 kWh/m^2/year nevertheless Kairouan region have an exergy content of about 1912 kWh/m^2/year. It is thought that this result is due to the ambient temperature of the region of Kairouan which is relatively high comparing to regions of the center.

However other group of regions amount a low value of solar exergy content such as Beja, Jendouba, Siliana, Bizerte, and Jendouba varying from 1800 kWh/m^2/year to 1950 kWh/m^2/year. These regions are located in the north of Tunisia. This leads to conclude that the energy solar radiation classification of the different regions in Tunisia is not sufficient and do not release the real solar potential of the regions. In this regard the 24 regions are classified regarding the exergy account, high solar exergy locations, medium solar exergy locations, and low solar exergy locations; these three grouping are expressed in Table 6, defining the exergy range and the energy range of each category. A new solar distribution map is developed in Fig. 2 according to this classification based on the exergy content rather than energy content.

Table 6: Different exergy category of the 24 studied regions.

Location	Exergy range (kWh/m^2/year)	Energy range (kWh/m^2/year)	Exergy category
South of Tunisia	2100–2270	2300–2400	High solar exergy
Center of Tunisia	1980–2050	2100–2200	Medium solar exergy
North of Tunisia	1800–1950	1950–2050	Low solar exergy

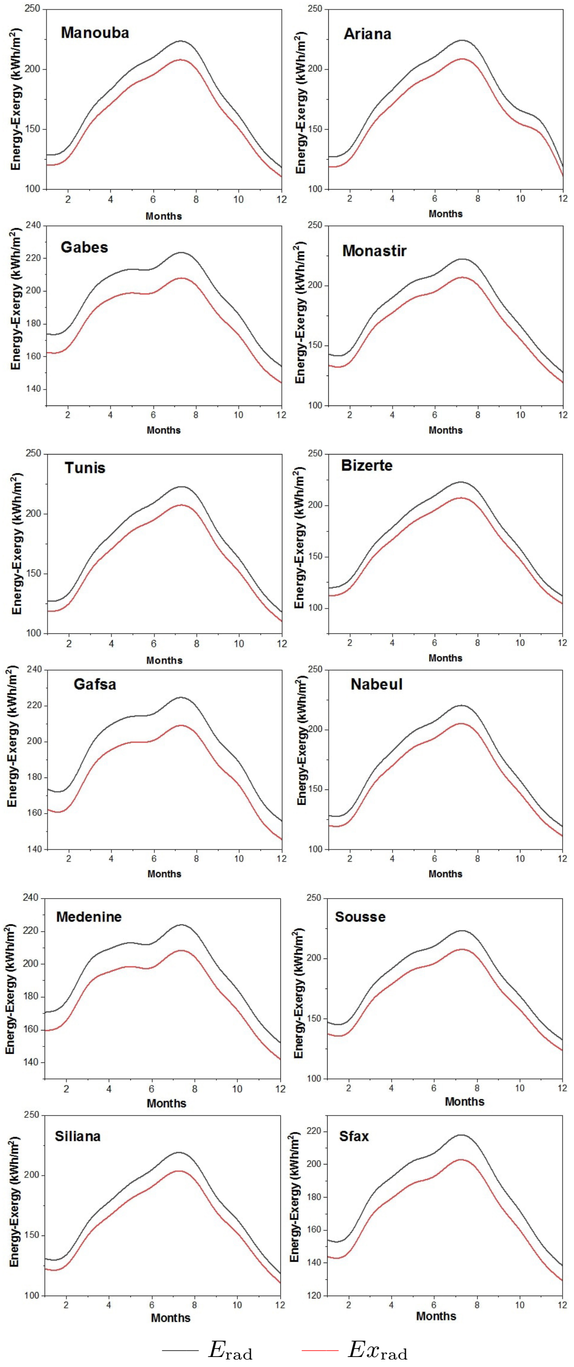

Fig. 1: For caption see facing page.

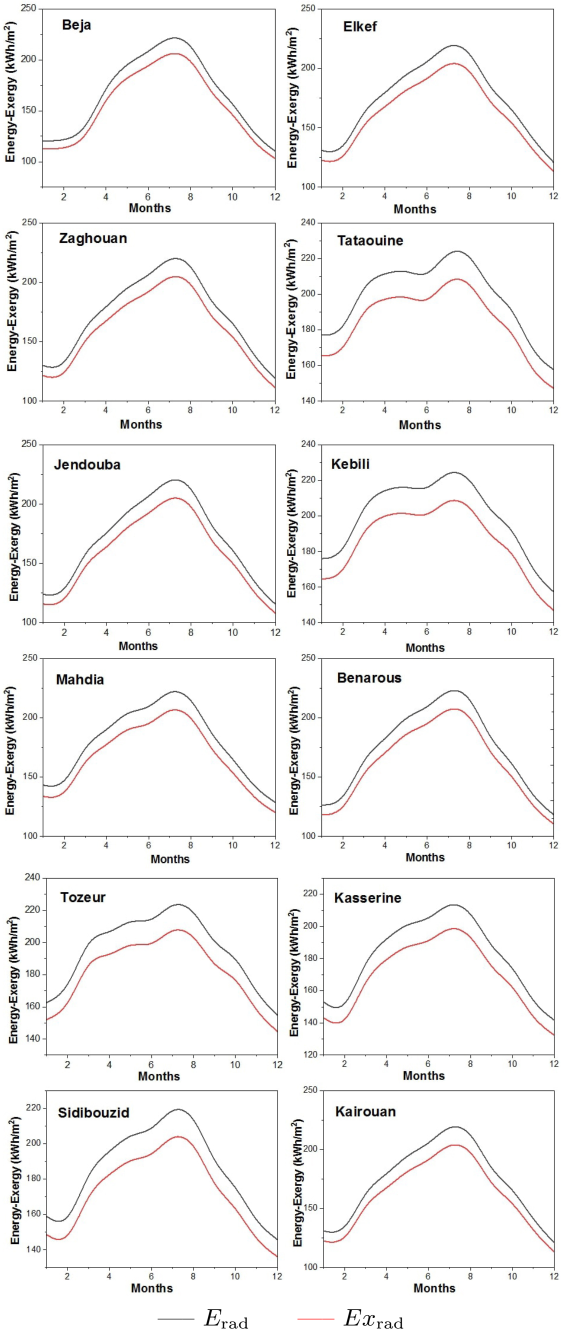

Figure 1: Variation of the monthly average values of the solar radiation energy and exergy for the 24 regions of Tunisia.

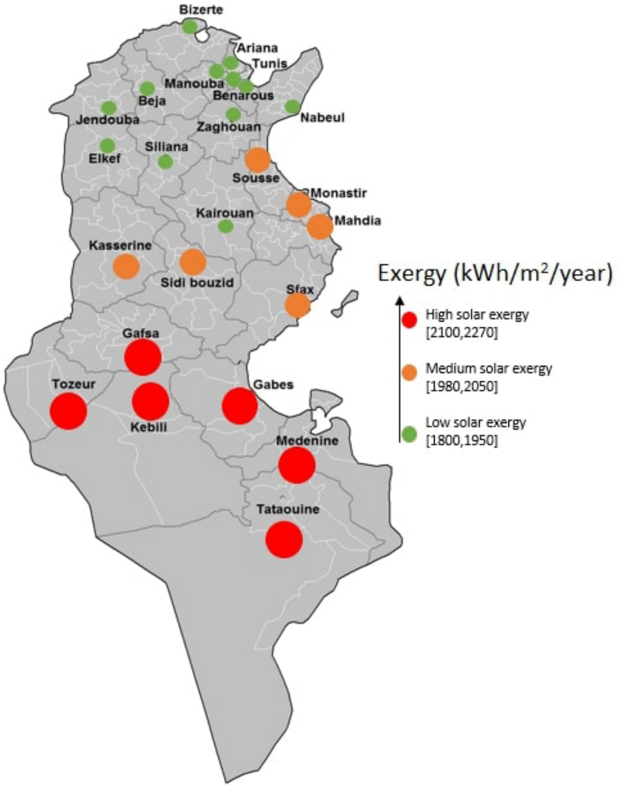

Figure 2: New zoning map based on solar exergy potential of the 24 studied regions in Tunisia.

By considering the result of Fig. 1, the effects of climate and seasons on solar radiation exergy can be investigated. It is observable that the solar radiation energy and exergy reach their highest values in the summer season, the maximum monthly solar radiation E_{rad} and the maximum monthly solar exergy Ex occur in July. It can be also remarked from this figure that lowest values of the solar radiation energy and exergy are obtained in the winter season, the minimum monthly solar radiation E_{rad} and the minimum monthly solar exergy Ex occur in December.

It is concluded from the status of solar radiation exergy in Tunisia, that southern regions are favourited for the various solar energy-related applications than the northern regions. The southern regions can be considered for thermal solar applications, while the central and northern regions can be privileged for photovoltaic.

5 Conclusion

In this study, a universal model for solar radiation exergy accounting was developed using Petela model for exergy efficiency and ASHRAE method for solar energy prediction. The following conclusions were drawn:

- It was found that the best regression model for the solar radiation energy accounting is the cubic one with an error value of 9.3414% and a correlation coefficient (R^2) equal to 0.9967.
- The optimal model to describe the Petela solar exergy coefficient (ψ_p) is the exponential regression model with an error value of 0.0048% and a R^2 equal to 1.
- A universal pattern for exergy solar radiation accounting is developed according to these two optimized regression models.
- The solar exergy potential in Tunisia is given based on the developed model. A new classification of regions based on exergy potential is provided.
- From Tunisia exergy potential account, it was found that exergy content in solar radiation is little lower than the solar radiation energy amounting. This presents the real useful potential of solar radiation.
- Tunisia regions were classified into three areas according to its solar exergy levels: High solar exergy amount going from 2100 to 2270 kWh/m^2 per year, medium solar exergy amount from 1980 to 2050 kWh/m^2 per year and finally, low solar exergy amount from 1800 to 1950 kWh/m^2 per year.

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