Energy 102 (2016) 550–558

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Solar and wind exergy potentials for Mars

Alfonso Delgado-Bonal [a, b, *], F. Javier Martín-Torres [a, c], Sandra Vázquez-Martín [a], María-Paz Zorzano [a, d]

[a] Division of Space Technology, Department of Computer Science, Electrical and Space Engineering, Luleå University of Technology, Kiruna, Sweden
[b] Instituto Universitario de Física Fundamental y Matemáticas, Universidad de Salamanca, 37008, Spain
[c] Instituto Andaluz de Ciencias de la Tierra (CSIC-UGR), Avda. de Las Palmeras n° 4, Armilla, 18100, Granada, Spain
[d] Centro de Astrobiología (INTA-CSIC), Ctra. Ajalvir km.4, Torrejón de Ardoz, 28850, Madrid, Spain

ARTICLE INFO

Article history:
Received 15 April 2015
Received in revised form
16 February 2016
Accepted 18 February 2016
Available online 15 March 2016

Keywords:
Second law analysis
Mars
Solar exergy
Wind energy
Renewable energy

ABSTRACT

The energy requirements of the planetary exploration spacecrafts constrain the lifetime of the missions, their mobility and capabilities, and the number of instruments onboard. They are limiting factors in planetary exploration. Several missions to the surface of Mars have proven the feasibility and success of solar panels as energy source. The analysis of the exergy efficiency of the solar radiation has been carried out successfully on Earth, however, to date, there is not an extensive research regarding the thermodynamic exergy efficiency of in-situ renewable energy sources on Mars. In this paper, we analyse the obtainable energy (exergy) from solar radiation under Martian conditions. For this analysis we have used the surface environmental variables on Mars measured in-situ by the Rover Environmental Monitoring Station onboard the Curiosity rover and from satellite by the Thermal Emission Spectrometer instrument onboard the Mars Global Surveyor satellite mission. We evaluate the exergy efficiency from solar radiation on a global spatial scale using orbital data for a Martian year; and in a one single location in Mars (the Gale crater) but with an appreciable temporal resolution (1 h). Also, we analyse the wind energy as an alternative source of energy for Mars exploration and compare the results with those obtained on Earth. We study the viability of solar and wind energy station for the future exploration of Mars, showing that a small square solar cell of 0.30 m length could maintain a meteorological station on Mars. We conclude that the low density of the atmosphere of Mars is responsible of the low thermal exergy efficiency of solar panels. It also makes the use of wind energy uneffective. Finally, we provide insights for the development of new solar cells on Mars.

1. Introduction

Solar radiation has been a source of energy in space missions as a power source for small satellites, for large structures such as the International Space Station, and for Solar System exploration. It has been very useful in Mars exploration, in particular during the Viking mission and in several Mars orbiters and rovers afterwards. The Mars Exploration Rover Opportunity was able to exceed the baseline mission duration from the 90 sols scheduled initially to more than 3500 sols, continuing nowadays.

The complexity of the rovers, and the energy demands of the experiments onboard have increased in the last decades. An example is the Curiosity rover in the NASA's MSL (Mars Science Laboratory) mission [1] currently operating on Mars. As the solar radiation intensity decreases with the square of the distance to the sun, solar energy might become inappropriate to maintain a complex spacecraft. For these reasons, the rover Curiosity is powered by a Radioisotope Thermoelectric Generator (nuclear power) and it is likely that the next rovers exploring Mars will use the same kind of energy source. Although nuclear power could be a partial and temporary solution [2], human colonization of Mars will require a perdurable and renewable source of energy. The transport of nuclear material from Earth to Mars implies large risk and costs. The existence of fossil energy, such as carbon or oil on Earth, seems unlikely to be found on Mars and its transport in spacecrafts is not feasible. Finally, geothermal energy is not feasible on Mars, since no significant geological activity has been recorded on the planet.

* Corresponding author. Instituto Universitario de Física Fundamental y Matemáticas, Universidad de Salamanca, 37008, Spain.
E-mail address: alfonso.delgado-bonal@ltu.se (A. Delgado-Bonal).

http://dx.doi.org/10.1016/j.energy.2016.02.110
0360-5442/

Nomenclature

A	solar cell area (m^2)
A_w	wind turbine area (m^2)
C_p	heat capacity at constant pressure (J $Kg^{-1}K^{-1}$)
C_{pow}	power constant of wind energy
d	declination (degrees)
D	transmission coefficient of radiation
E	energy from solar radiation (Wh)
Ex	exergy of solar radiation (Wh)
Ex_e	electric exergy of solar radiation (Wh)
Ex_{th}	thermal exergy of solar radiation (Wh)
h_{rad}	radiative heat transfer coeff. (W m^2 K^{-1})
h_w	wind convection heat transfer coeff. (W m^2 K^{-1})
$h_{w,N}$	h_w at NOCT (W m^2 K^{-1})
L	latitude (degree)
Ls	solar longitude (degree)
$\dot{m}_a$	mass flow rate (kg s^{-1})
P	power (W)
P_r	performance ratio (%)
$\dot{Q}_{cell}$	thermal power (W)
r	Mars distance (AU)
r_{av}	average distance Mars-Sun (AU)
t	time (hours)
T_a	ambient temperature (K)
$T_{a,N}$	ambient temperature at NOCT (K)
T_c	solar cell temperature (K)
$T_{c,N}$	solar cell temperature at NOCT (K)
T_g	ground temperature (K)
T_{ref}	reference temperature at NOCT (K)
T_s	temperature of the Sun (K)
T(D,z)	Pollack transmission coefficient
u	free-stream velocity of air (m s^{-1})
U_L	overall loss coefficient
u_N	u at NOCT (m s^{-1})
$U_{L,N}$	overall loss coef. at NOCT
z	zenith angle (degree)

Greek Symbols

ϕ	irradiance (W m^{-2})
ϕ_{TOA}	ϕ at Top of the Atmosphere (W m^{-2})
ϕ_{surf}	ϕ at surface (W m^{-2})
ϕ_N	NOCT radiation (W m^{-2})
ψ	photovoltaic exergy efficiency
η	electric efficiency
η_{ref}	reference cell electric efficiency
ρ	density (kg m^{-3})
σ	Stefan's constant (W m^{-2} K^4)
τ	transmittance of glazing

The objective of this paper is to investigate the efficiency of solar energy on Mars and in order to do so, it becomes necessary to analyze not only the radiation reaching Mars but also its environment.

In the last decades, the mechanical engineer community put much emphasis in providing a framework to analyze the thermodynamic processes properly. Classically, the analysis of a process using the first law of thermodynamics has been applied to thermodynamic problems, appealing to energy conservation rules. However, the second law of thermodynamics is not applied under that approach and the description of the processes can be improved by its inclusion, carrying out what has been called “second law analysis”. The second law introduces the concept of entropy and deals with the heat lost in a process, i.e., is related to the environment and it is of importance in the quality of the radiation. These second law analysis are developed to minimize the heat lost and maximize the obtainable work. The maximum obtainable work –or availability– is described by the concept of exergy (from the Greek exo – $\varepsilon\xi o$ – and energia–$\varepsilon\nu\varepsilon\rho\gamma\iota\alpha$–); the exergy of a thermodynamic system is a measure of the potential work of the system [3]. For a detailed historic description of the exergy concept, refer to [Rezac and Metghalchi, 2004] [4].

The exergy concept has been applied mainly in engineering thermodynamics, and resulted in a more effective method to analyze heat transfer than energy analysis [5]. In particular, the idea of exergy was also investigated in relation to solar radiation, proving to be a very successful area of research with theoretical and engineer applications. The early ideas of Petela [6] and Spanner [7] in 1964 started an ongoing research on the exergy of radiation, providing methods to evaluate the maximum conversion efficiency of solar radiation with different approaches, including direct and diffuse radiation, blackbody approximations, dilute radiation or semi transparent medium [8–11]. Although Planck derived originally the expression for the radiation intensity for a monochromatic radiation beam at thermodynamic equilibrium, it has been demonstrated to hold for non blackbody radiation at a non equilibrium condition as well [12–15].

The exergetic analysis combines the two laws of thermodynamics to analyse the energy exchange in a particular environment, providing a powerful tool to investigate the performance of a device in a system. It has been applied extensively on Earth, applied in studies in Europa, US, India and Turkey for example [16,17,5,18,19]. The exergy concept has been applied to improve the analysis of thermal processes in many situations considering the environment [20], as for example in solar collectors (Flat-plate, Hybrid PV/T systems or Parabolic) [21] under different meteorological conditions [22]. Besides simple implementations of solar collectors, more complex and more efficient alternatives have been studied for heating/cooling applications [23], which provide a more efficient use of solar radiation.

In this paper, we will focus our study to flat-plate collectors in Mars. Even though parabolic collectors for example could increase the obtained energy on the planet, it has never been tested on Mars due to the technological difficulty of transporting the panels. In the case of Hybrid PV/T systems, which convert solar energy to electric and thermal energy, they require a fluid to operate and have not been implemented on Mars yet either.

To accomplish our goal to analyze the exergy of solar radiation on Mars, it is necessary to know the radiation field environment that reaches the planet. In Section 2 we determine the solar radiation reaching Mars TOA (Top of the Atmosphere) and surface, necessary to determine the obtainable energy from solar radiation, considering the current composition of the atmosphere and modelling the Martian orbital position to determine the radiation at different seasons and locations on the planet. In our analysis, we have used typical values for solar panels to provide accurate values of the obtainable energy by solar stations on Mars.

To continue the analysis, the environmental properties of Mars must be considered in order to provide a comprehensive analysis of the solar exergy on the planet. Even though exergetic analysis is a universal tool based on the laws of thermodynamics, the solar exergy on Mars has not yet been studied in depth [2]. In this paper, we evaluate the spatial and temporal evolution of the exergy on Mars based in satellite and in-situ rover data. The eccentricity of Mars is 0.09331 and the maximum distance to the sun (aphelion) is 1.665861 AU. As the distance increases, the intensity of the solar flux reaching the surface decreases, reducing the capabilities of the solar powered spacecrafts. Hence, the exergy of radiation will be different at different seasons during a Martian orbit. Not only that, the exergy of radiation will change with location; and for a given location, on a daily basis. Using the environmental data provided by the REMS (Rover Environmental Monitoring Station) instrument [24] onboard the Curiosity rover [1] we calculate the exergy efficiency of solar radiation on a single location at different seasons in a daily basis. The knowledge of the temperature, pressure and density of the atmosphere is used along with the radiation reaching the surface of the planet to determine the exergy efficiency at different hours.

The Curiosity rover landed at crater Gale (4.49°S, 137.42°E) on Mars. Although Curiosity data are undoubtedly valuable, they are representative of a single location on the planet. In order to analyse the maximum exergy efficiency of radiation at different latitudes on the planet, we use the data provided by the TES (Thermal Emission Spectrometer) instrument onboard the MGS (Mars Global Surveyor) spacecraft [25,26] to determine the maximum temperature of the environment through a complete Martian year. In Section 3 we explain the formalism used in this work to determine the exergy of radiation and show the results of the exergy efficiency of solar radiation in Mars.

Another energetic alternative for Mars exploration and future human colonization of the planet could be wind energy. Wind stations are an excellent alternative on Earth and their use on other planets could be a potential source of renewable energy. We have considered that alternative and we show the results of the wind energy analysis on Section 4.

In Section 5 we compare the results of solar exergy efficiency between the Earth and Mars, providing insights for future work and developments that could help to increase the efficiency of renewable energy sources on Mars. Finally in Section 6 we summarize the main results of this investigation.

2. Solar energy on Mars

A solar cell cannot convert all the received energy from solar radiation into electrical energy, and the solar energy reaching a photovoltaic (PV) panel that cannot be converted in other forms of energy heats it. In general, the obtainable energy (E) from solar radiation reaching a panel is:

$$E = A \cdot \eta \cdot \phi \cdot P_r \tag{1}$$

where A is the total solar panel area (m^2), η is the solar panel yield (%) and ϕ (W/m^2) is the solar irradiance reaching the panel. In this equation, P_r is the performance ratio, a coefficient accounting for the losses in the conversion process, which is usually between 0.5 and 0.9 [27]. In an ideal process, the performance ratio would be equal to 1.

The solar panel yield, η, determines the obtainable energy by a solar panel per unit of area. It represents the ratio between the obtained energy and the total energy reaching the panel. η is called first law efficiency or energy efficiency and it is directly determined by the type of solar cell and the fabrication processes. The maximum yield obtained nowadays is about 45% of the radiation reaching the panel [28]. Although this value was obtained under laboratory circumstances and the commercial yields are much lower, in our calculations we will determine the maximum obtainable work under the best case scenario considering 0.45 as the yield value. The performance ratio, P_r, is the ratio between the obtained energy and theoretically calculated values. It depends on the orientation of the panel, incident solar radiation, electronics, and thermal and conduction energy losses. We consider a nominal value of 0.75 for the calculations performed in this paper.

In order to calculate the irradiance values (ϕ) in different Martian orbital positions, we have modelled the irradiance reaching Mars TOA (Top of the Atmosphere) in W m^{-2} according to the equation [29]:

$$\phi_{TOA} = 592\left(\frac{r}{r_{av}}\right)^2 = 592\left(\frac{1+0.0934\cdot\cos(L_s-250^\circ)}{0.9913}\right)^2 \tag{2}$$

where r_{av} is the average distance Mars-Sun (1.52 AU), and L_s is the solar longitude (Mars–Sun angle) measured from the northern hemisphere, which is $L_s = 0°$ in vernal equinox.

The intensity reaching the surface without considering the atmospheric absorption could be calculated as $\phi_{surf}=\phi_{TOA}\cdot\cos(z)$, where z is called zenith angle and can be determined as:

$$\cos(z) = \sin(d)\cdot\sin(L) + \cos(d)\cdot\cos(L)\cdot\cos(2\pi t/24.6) \tag{3}$$

with d the declination angle, L the observational latitude and t the time of day (from −12.3 h to +12.3 h, being noon equal to zero). The declination angle can be easily related with the Ls as $\sin(d) = \sin(25.2°)\sin(L_s)$, where 25.2° is the eccentricity of the planet.

The radiation is scattered and absorbed during its passage through the atmosphere, and those effects must be considered for a correct calculation of the irradiance. The Beer's Law is usually used to calculate the direct component of the irradiance at ground level, being $\phi_{surf} = \phi_{TOA}\cdot exp(-D/\cos(z))$, where D is the transmission coefficient for the direct component. However, the Mars atmosphere is very rich in dust and the scattering becomes an important physical process in the radiative transfer on the atmosphere. The diffuse energy can be also used to generate electricity in the solar cells [9], and a precise treatment of the radiation should be considered. In this paper, we will use the Pollack transmission coefficients [30] for an optical depth of D = 0.3, which is consistent with the latest measurements by the cameras on the rover Curiosity [31]. Considering all these processes, the radiation on the surface can be calculated as:

$$\phi_{surf} = \phi_{TOA}\cdot\cos(z)\cdot T(D,z) \tag{4}$$

where T(D,z) is the Transmission Coefficient that is a function of optical depth and solar zenith angle [29].

The mean irradiance on Earth is 1380 W/m^2 at the top of the atmosphere. Geometrically scaling that value to Mars, for an average distance of 1.524 AU, we obtain about 600 W/m^2 at the top of the atmosphere, which is an upper limit of the radiation that could be extracted by a perfect device on Mars without the consideration of the atmosphere. The radiation reaching the surface that could be converted by solar cells in Gale crater location at Mars is calculated using the equations described in this section. The daily evolution for different orbital positions is shown in Fig. 1 in W/m^2.

3. Exergy efficiency of solar radiation

Thermodynamics is mainly ruled by two laws. The first law of thermodynamics establishes that energy is a conserved quantity that can be divided into heat and work. Energy analysis is a typical

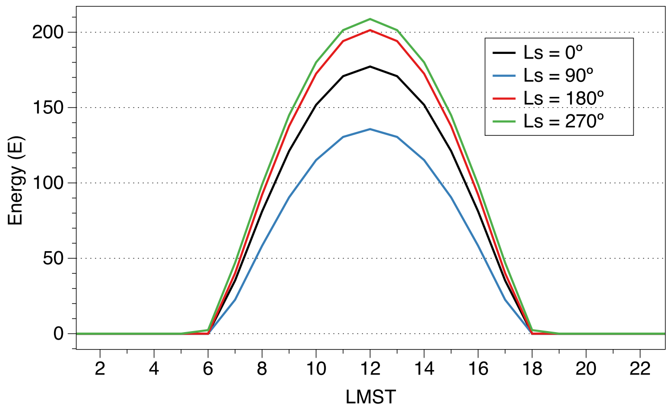

Fig. 1. Obtainable solar energy (E) in crater Gale as a function of Local Mean Solar Time (LMST), and season.

approach to a process and it is useful to determine the efficiency of energy conversion, using the rule of energy conservation.

The second law of thermodynamics introduces the concept of entropy. Contrary to energy, entropy is a non-conserved magnitude and is related to the quality of the energy. Combining both laws, it is possible to define the exergy, a magnitude introduced to improve the energy analysis. Exergy analysis is based on both the first and the second laws of thermodynamics and provides an advanced tool for engineering process evaluation, providing a value for the maximum ability to perform work [32]. It depends not only on the energy source but also on the environmental parameters that determine the heat exchange between the radiation, the device and the environment.

A complete knowledge about the system is needed to determine the maximum work obtainable from a system –solar radiation in our case–. Solar exergy analysis has been carried out on Earth but it has not been extensively applied to Mars up to date due to the limitation of available environmental data.

The meteorological stations on Mars are very limited, as well as our knowledge about the environment. In this paper we use the data provided by the REMS instrument onboard the Curiosity rover to calculate the exergy efficiency of solar radiation on Mars. REMS data represent the most comprehensive set of values up to date and currently includes more than a Martian year, containing values of temperature, wind, pressure and humidity at ground level and at 1.6 m over ground. Once the environmental variables are known, it is possible to analyse the efficiency of the solar energy conversion at different orbital positions.

REMS provides values of the thermodynamic variables for a single location on Mars. In order to extend our study to the whole planet, we have used the values measured from satellite by TES; in that way, we are able to determine the exergy efficiency for a whole year at different latitudes, but with less temporal resolution.

The formal definition of exergy relies on the definitions of energy and entropy. The Planck's law to determine the energy of a blackbody is:

$$L_\nu = \frac{h\nu^3}{c^2}\frac{1}{e^{\frac{h\nu}{kT}}-1} \tag{5}$$

Planck also presented the expression of the entropy content of radiation [33]:

$$S_\nu = \frac{k\nu^2}{c^2}\left\{\left(1+\frac{c^2L_\nu}{h\nu^3}\right)\log\left(1+\frac{c^2L_\nu}{h\nu^3}\right)-\frac{c^2L_\nu}{h\nu^3}\log\frac{c^2L_\nu}{h\nu^3}\right\} \tag{6}$$

Using the two laws of thermodynamics, Rant [34] coined the term exergy that represents the maximum quantity of work that can be produced in some given environment [35], in an attempt to determine theoretical limits of performance of various thermodynamic components and systems. With that definition and the last two equations, Candau [36] defined the spectral radiative exergy intensity (exergy of radiation) as:

$$Ex_\nu = L_\nu(T_\nu) - L_\nu(T_0) - T_0[S_\nu(T_\nu) - S_\nu(T_0)] \tag{7}$$

As the atmosphere of Mars is not very thick, it is possible to analyze the exergy assuming blackbody radiation. Integrating Eq. (5) we obtain the Stefan–Boltzmann law which states that the energy is proportional to the fourth power of the temperature, $E = \sigma T^4$, and integrating Eq. (6) the entropy depends on the third power of the temperature, $S = \frac{4}{3}\sigma T^3$.

If the emission of radiation by the planet is not considered, the terms depending on T_0 can be neglected and we obtain the equation proposed by Spanner [7] to determine the exergy:

$$Ex = \sigma T_s^4\left(1-\frac{4}{3}\frac{T_a}{T_s}\right) \tag{8}$$

where σ is the Stefan's constant, T_a the ambient temperature and T_s the Sun's temperature. Considering the radiation emitted by the body itself, we obtain a more accurate description of the exergy of radiation:

$$Ex = \sigma T_s^4\left(1-\frac{4}{3}\frac{T_a}{T_s}+\frac{1}{3}\frac{T_a^4}{T_s^4}\right) \tag{9}$$

This last expression was proposed by Petela in 1964 [6] and was confirmed later by other researchers [37,38], although other authors, like Jeter [10], proposed different equations arguing that the maximum obtainable work is established by a Carnot expression. Candau [36], based on thermodynamical arguments, demonstrated theoretically that the expression for the conversion of solar radiation into work is the one proposed by Petela [6].

The exergy efficiency of a PV cell can be analysed using the exergy of radiation. Following the formalism presented at Le Corre et al. [16] improved to use the Petela's expression, the exergy content can be divided in two parts: an electrical part, Ex_e, that depends on the fabrication process and is determined by the yield η (electric efficiency), and the thermal part, Ex_{th}, which depends on the interaction between the cell and the environment. Then, using the Joshi's approach for the determination of the thermal exergy [11], the expression to determine the total exergy efficiency reads:

$$\psi = \frac{Ex_e + Ex_{th}}{Ex} = \eta + \frac{\left(1-\frac{4}{3}\frac{T_a}{T_c}+\frac{1}{3}\frac{T_a^4}{T_c^4}\right)\dot{Q}_{cell}}{\left(1-\frac{4}{3}\frac{T_a}{T_s}+\frac{1}{3}\frac{T_a^4}{T_s^4}\right)\cdot\phi A} \tag{10}$$

where T_c is the temperature of the solar cell. The second term of this expression is determined by the interaction between the cell and the environment. The thermal power, $\dot{Q}_{cell}$ is calculated as proposed by Joshi et al. [11]:

$$\dot{Q}_{cell} = \dot{m}_a\cdot Cp\cdot(T_c - T_a) \tag{11}$$

where $\dot{m}_a = \rho u A$ is the mass flow. As can be seen in the latest expressions the thermal efficiency of the conversion depends on the heat lost by the panel in a particular environment, while the electrical part depends only on the fabrication process. For a given panel, the parameters that determine the efficiency of the transformation are the density of the atmosphere (ρ), its composition (through the heat capacity, Cp) and the refrigeration processes (u,$\Delta T = T_c - T_a$), which will determine ultimately the operating temperature of the cell and the thermal power.

The current Martian atmosphere is composed mainly by CO_2 (98% of the total composition). We assume in our calculations that the atmosphere is only composed by CO_2, with a heat capacity varying from $C_p = 0.709$ ($m^2\ s^{-2}\ K^{-1}$) at 175 K to $C_p = 0.791$ ($m^2\ s^{-2}\ K^{-1}$) at 250 K. In comparison with our atmosphere, the Martian atmosphere is extremely thin, with a density of about $\rho = 0.020$ kg m^{-3} compared with 1.225 kg m^{-3} on Earth. In this work, we assume that the Martian atmosphere behaves as an ideal gas when we determine the value of the density as a function of the temperature and pressure.

The T_c (temperature of the cell) is usually different than the T_a (ambient temperature). For the Martian environment, the refrigeration is produced by forced convection and radiation, and its importance depends on the configuration of the solar panel. We consider two cases: a solar cell lying on the ground, as those in the Viking landers; and a flat panel at 1.6 m above the surface, as those mounted on the Mars Exploration Rovers (Spirit and Opportunity). For the first case, we consider T_c as the surface temperature measured by REMS. For the second case, the temperature is evaluated with the following expression [39]:

$$T_c = \frac{T_a + \left(\frac{\phi_s}{\phi_{s,N}}\right) \frac{U_{L,N}}{U_L}\left(T_{c,N} - T_{a,N}\right)\left[1 - \frac{\eta_{ref}}{(\tau\alpha)}\left(1 + \beta_{ref} T_{ref}\right)\right]}{1 - \frac{\beta_{ref}\eta_{ref}}{(\tau\alpha)}\left(\frac{\phi_T}{\phi_N}\right) \frac{h_{w,N}}{h_w}\left(T_{c,N} - T_{a,N}\right)} \tag{12}$$

where T_a is the ambient temperature measured by REMS at 1.6 m above the ground, u is the wind velocity and ϕ is the irradiance on the panel. The determination of the operating temperature depends on the solar irradiance heating the panel and the refrigeration processes that release heat to the environment. The overall loss coefficient (U_L) in Eq. (12) include the heat released by wind convection (h_w) and by radiation (h_{rad}), $U_L = h_w + h_{rad}$ [40].

In this paper we will use the Nominal Operating Cell Temperature (NOCT) and reference values cited in [39], which are summarized in Table 1. Using an iterative process until convergence (6 steps), it is possible to approximate Eq. (12) into an accurate linear expression for the Martian environment, depending on the ambient temperature (T_a), solar irradiance (ϕ) and wind velocity (u) [41]:

$$T_c = 1.00116 \cdot T_a + 0.0313174 \cdot \phi - 0.108832 \cdot u \tag{13}$$

3.1. Daily and seasonal solar exergy efficiency at a location on Mars: the Gale crater

The thermal efficiency depends on the mass flow rate, which depends itself on the atmospheric density and wind velocity. The atmospheric density for the different seasons was calculated using REMS measurements and considering the ideal gas approximation. REMS is located on crater Gale (4.49°S, 137.42°E), and contains sensors to determine the ground and air temperature of the environment. The ATS (Atmospheric Thermal Sensor) is located at 1.6 m over the ground and provides measurements on the air temperature. The GTS (Ground Temperature Sensor) measures the temperature values of the ground (note that $T_g > T_a$ during the daytime and $T_a > T_g$ at nighttime).

The temperature of the solar panel results on the competition of the heating by solar radiation and the heat losses (cooling) by wind convection and radiation. The heat loss by radiation depends itself on the temperature of the radiating body (the panel); in order to compute it, we have determined the temperature of the body at each hour using an iterative method in Eq. (12) until convergence, starting with a temperature 30 K over the ground temperature [41]. The heat loss by wind convection is directly proportional to the wind velocity. The best estimations of the wind on Mars predict wind speeds between 10 m s^{-1} and 4 m s^{-1} [42]. During extreme events such as dust devils, the wind speed can increase until 25 m s^{-1} , with an average of 12 m s^{-1} [43]. However, in those events the dust storm would block the majority of the radiation and the obtainable energy would be very low. Performing a sensitivity analysis of Eq. (12) we determine that the effect of the wind speed is much less important than the radiation reaching the panel. At 20 m s^{-1} the refrigeration on the solar panel is only about 2 K. In this paper, we use 5 m s^{-1} in our calculations of the exergy of solar radiation.

Fig. 2 shows the thermal exergy efficiency (ψ) of solar radiation on Mars for a square solar panel of 1 m length in two different scenarios. In Fig. 2 (a) we assume that the solar panel is at the same temperature than the ground, i.e., the measurements provided by the GTS on REMS. This situation will occur when the panel is directly lying on the ground, as for example in the case of the Viking landers. In Fig. 2 (b) we determine the temperature of the panel using Eq. (12) and the ambient temperature provided by the ATS on REMS at 1.6 m, i.e., the case of the Spirit and Opportunity rovers for example. In both cases, the efficiency of the radiation is calculated for different orbital positions on Mars.

The thermal efficiency of the panel on the ground is larger than the case of the panels standing at 1.6 m. When the panel is lying on the ground, the temperature difference between the temperature of the cell and the ambient temperature is larger, increasing the thermal power. This implies an increase in the exergy and therefore in the exergy efficiency coefficient. Fig. 2 (a) shows negative values of the efficiency during the first hour in the morning (i.e., the panel is giving energy to the atmosphere). The explanation is that after the photons reach the panel, it is still at a lower temperature than its environment. The panel is heated by the solar photons and, after 1 h, the temperature of the cell is higher than the air temperature, and it can obtain energy from radiation instead of giving it.

3.2. Seasonal solar exergy efficiency as a function of location on Mars

In the previous section we have analysed the exergy efficiency of solar energy in a particular location on Mars, the crater Gale, that is located near the equator of the planet. In order to determine the exergy efficiency of solar radiation on Mars as function of location and season, we have used the values of surface temperature provided by the TES (Thermal Emission Spectrometer) instrument onboard MGS (Mars Global Surveyor). We have organized the temperatures of Mars at different latitudes on the planet at different orbital positions, and selected the maximum temperature as the T_a (ambient temperature) for our analysis (which usually corresponds to noon) in order to determine the exergy efficiency of

Table 1
NOCT reference values.

u_{NOCT}	1 m/s
$T_{a,NOCT}$	20°C
$\phi_{T,NOCT}$	800 W
$T_{c,NOCT}$	47°C
η_{ref}	0.12
β_{ref}	0.004°C^{-1}
T_{ref}	25°C
$\tau\alpha$	0.9

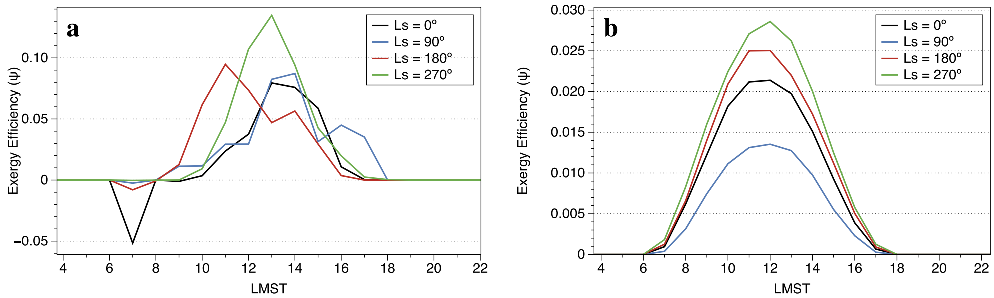

Fig. 2. Calculations of daily efficiency for different seasons on Mars considering two solar panel location scenarios: (a) Ground level, on the left, and (b) 1.6 m height, on the right. Note the different scale in the efficiency axis.

the radiation on the planet. In this study, we have not taken into account the effect of the topology on Mars, which could provide a second-order approximation to the values presented in this paper.

Fig. 3 (a) shows data from the TES instrument and Fig. 3 (b) the exergy efficiency of radiation calculated using the model explained above. The results are shown for a wind velocity of 5 m s^{-1} for Martian year 24 (2000–2001) for a constant density of 0.02 kg m^{-3}. The maximum temperature is located in the zone near −23° as a consequence of the eccentricity of the planet, with a maximum value close to 250 K.

Analyzing the values obtained above, we see that the thermal efficiency on Mars is as low as 0.012 for the situation where the panels are located at 1.6 m of altitude, and the maximum value is about 0.1 in the case of the panels lying on the ground. In general, the efficiency of solar conversion on Mars is between 0 and 0.02, as represented in Fig. 3, and it is higher if the panels are lying directly on the ground.

4. Wind energy

Another renewable source of energy which is used extensively on Earth is the wind power or wind energy. The ability to extract electrical energy using the wind has been used on Earth since more than a century ago, and its use is growing nowadays around the world. Wind energy is a renewable source of energy which consumes little land, is relatively inexpensive, is free of greenhouse gases and it could be an alternative for the exploration of the Solar System.

The obtainable electrical energy from wind can be expressed as:

$$E = \frac{1}{2}\rho A_w t u^3 \tag{14}$$

with A_w the wind turbine area (m^2), t the time (s) and u the wind speed (ms^{-1}). By applying momentum theory to windmills, it can be found that there is an upper limit in the conversion; the maximum power that an ideal windmill could extract is limited to a 59.3% of the total energy, which is called Betz's Law [44]. This law is independent on the atmosphere, and it also applies to Mars. The extractable power from wind can be calculated as:

$$P = \frac{1}{2}\rho A_w u^3 C_{pow} \tag{15}$$

where C_{pow} is the power coefficient with the upper limit of 0.593. For the windmills available nowadays the typical value is between 0.3 and 0.45. The power curve is dependent on the cross-sectional area perpendicular to the flow (A_w), the velocity of wind (u), and the density of the atmosphere (ρ).

Fig. 4 represents the power curve for a hypothetical 100 kW wind turbine with a 18 m diameter rotor and a hub height of 30 m

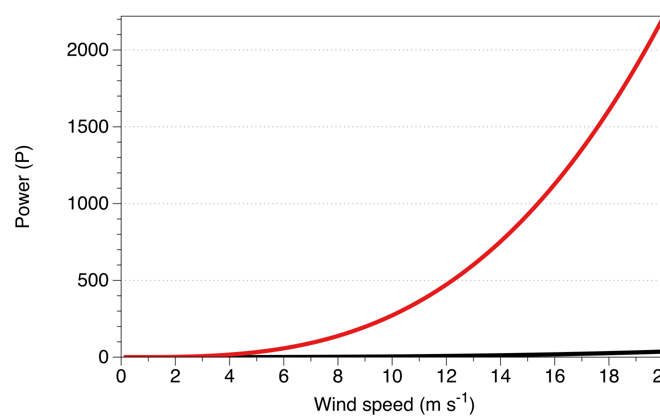

Fig. 4. Wind power on Earth (red line) and Mars (black line) in kW. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

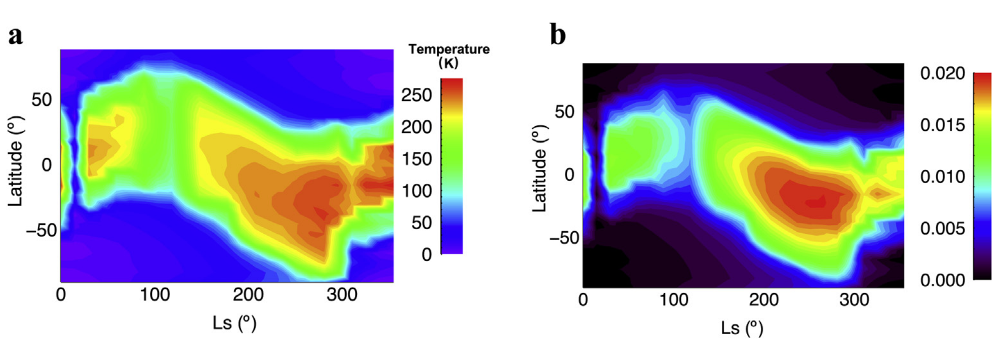

Fig. 3. (a) Martian map of maximum temperature for year 24 (left) and (b) solar conversion efficiency in a Martian orbit (right).

on Earth and Mars. We have selected this kind of windmill to be able to compare our results with those available in the literature [45] [46]. In our calculations, we assume a power constant of $C_{pow} = 0.45$ to provide maximum power values that nowadays windmills could generate.

At an altitude of 30 m, the wind velocities on Mars are expected to be higher than in the planetary boundary layer, with values of 20 m s^{-1}. Even in that case, the power produced on Mars would be less than 35 kW, compared with the 2200 kW generated on Earth with the same kind of windmill. Also, at those altitudes, the Martian density will be lower (scaling exponentially) as well as the power produced.

The low density of the Martian atmosphere is not able to move the windchill strongly enough to be used a realistic source of energy. Generation of energy during dust storms, when winds are faster and the density increases, could provide more power. However, these dust storms are not frequent —not a convenient way— to maintain a spacecraft or human beings, and the winds are very turbulent and could damage the installation.

5. Discussion

Further steps in human exploration and colonization of Mars will require a perdurable and renewable source of energy. NASA plans to start human colonization on the planet in 2035. If so, the future colonies will require energy. We discuss here the power produced by solar and wind stations on Mars. The maximum energy provided by the current solar panels and windmills is presented in Tables 2 and 3. For solar energy, we have assumed an efficiency of $\eta = 44.7\%$ for the solar cells, with a performance ratio of 0.75 and a panel area of 1 m^2. For wind energy, we have assumed a $C_{pow} = 0.45$ and an atmospheric density of 0.02 kg m^{-3}. Note that the obtained values are linearly proportional to the area of the panel.

From Tables 2 and 3 we conclude that solar energy on Mars is a much better choice than windmills. Besides the fact that wind energy production is very low on Mars, solar devices present several benefits against windmills. In general, solar panels do not contain moving parts which can be degrade with dust, and the size of the device is considerable smaller than windmills, which is translated into less payload in the spacecraft being therefore cheaper.

For example, the REMS instrument onboard Curiosity has a power consumption of 10.08 W when all sensors are measuring (with ASIC heating) [24]. From our calculations, a windmill of 2.5 m of diameter rotor could provide 11 W with a constant wind speed of 5 m/s. Meteorological stations on Mars will be, however, more probably constructed based on solar energy. The difficulties of constructing a 2.5 m of diameter rotor windmill are numerous and its maintenance extremely complicated. Using solar energy to accomplish that power, one would require a square flat panel of 0.30 m of length with a battery, which could provides 12.7 W.

As has been discussed in the introduction, more efficient devices can be developed for the use of solar radiation [23]. However, with the level of technology that is currently available and the difficulties and costs of planetary missions, flat solar panels are the only feasible devices for Mars applications nowadays. Nevertheless, as technology is improving every day, future research should be done in more efficient devices for solar energy conversion on Mars, facing the technological challenges of the planet.

Table 3
Wind power (W) as a function of velocities and rotor diameters on Mars ($C_{pow} = 0.45$).

	1 m	5 m	10 m	15 m
3 m/s	0.38	9.54	38.15	85.84
5 m/s	1.77	44.16	176.63	397.41
10 m/s	14.13	353.25	1413.00	3179.25
15 m/s	47.69	1192.22	4768.88	10730.00
20 m/s	113.04	2826.00	11304.00	25434.00
25 m/s	220.78	5519.53	22078.10	49675.80

In order to understand the obtained values of the second law efficiency of radiation on Mars is necessary to compare them with known situations. In our paper, we have analyzed Mars in a particular location (crater Gale) as well as the seasonal behaviour as a function of the latitude. In the knowledge of the authors, there is not more research on the topic to compare our results with, but is possible to compare with the exergy efficiency on Earth. In our paper, we have obtained values for the exergy efficiency close to zero, which are slightly larger in those situations where the panel is situated in ground level. The exergy efficiency has been calculated on Earth following a procedure similar to the one presented in this paper, obtaining typical values between 20 and 30% [16] for a flat-panel.

The development of exergy efficiency maps on Earth is useful for the decision making processes. It is reasonable to look for those locations where the exergy efficiency is larger, since the difference between locations is noticeable. However, in view of our results, the exergy efficiency on Mars is almost uniform and close to zero in the whole planet, and therefore the exergetic thermodynamic arguments for the installation of solar panels is not as important as it is on Earth. For Mars, the technological limitations and radiation availability should be more important factors than the exergy of the location.

The exergy efficiency is a function of the radiation reaching the panel; the higher the radiation, the higher the exergy. As radiation intensity is higher on Earth than on Mars, it is expected that the exergy efficiency will be bigger on Earth. However, this is not the main reason why the exergy efficiency on Mars is close to zero. In view of our results, it is useful to simplify the equations presented in this paper to analyze the causes of the low exergy efficiency in Mars.

Eq. (13) resembles to a linear expression used on Earth to calculate the temperature of a solar cell [39] except by the inclusion of a “refrigeration” term depending on the wind speed. By doing a sensitivity analysis, it can be seen that at wind speeds of 20 m/s, which are very high and usual on Mars, the last term in Eq. (13) contributes only about 2 K. Neglecting that term, the expression seems similar to the one used on Earth:

$$T = T_a + k_r \cdot \phi \tag{16}$$

where k_r is called Ross coefficient.

Table 2
Daily solar power (W) production for a 1 m^2 panel ($\eta = 0.447$; Pr = 0.75) as a function of latitude and season.

	−60°	−45°	−30°	−15°	0°	15°	30°	45°	60°
Ls = 0°	578.3	877.4	1108.0	1253.5	1296.3	1253.5	1108.0	877.4	578.3
Ls = 90°	18.2	221.2	505.9	793.8	1034.0	1220.2	1326.2	1357.8	1335.8
Ls = 180°	657.2	997.0	1259.1	1424.4	1278.3	1424.4	1259.1	997.0	657.2
Ls = 270°	1899.4	1930.5	1885.8	1735.0	1470.2	1128.7	719.3	314.6	25.8

Including this approximation in Eq. (10), along with the definition of Thermal power 11, we have a simplified equation:

$$\psi \simeq \eta + \frac{\left(1 - \frac{4}{3}\frac{T_a}{T_c} + \frac{1}{3}\frac{T_a^4}{T_c^4}\right)\rho u C_p k_r}{\left(1 - \frac{4}{3}\frac{T_a}{T_s} + \frac{1}{3}\frac{T_a^4}{T_s^4}\right)} \quad (17)$$

The exergy efficiency depends on the temperature ratio between the cell and the ambient, which ultimately depends on the radiation intensity according to Eq. (16), but also depends linearly on the density of the atmosphere and the wind speed. Analyzing the values of the different terms, it is found that the value of the product of the density and the wind speed ($\rho \cdot u$) determines the value of the exergy efficiency. On Earth, a typical value of the density at a sea level at 15° latitude is 1.225 kg m^{-3}, and wind speed is typically in the range [0–50] m/s. On the contrary, on Mars, the density is 0.02 kg m^{-3} and the wind speed is about 5 m/s. The interaction between the cell and the environment is therefore very different in both situations, leading to very different values for the exergy efficiency of radiation.

6. Conclusions

The use of solar energy as a source of power on Solar System exploration has demonstrated to be an excellent choice. It provides enough energy to maintain rovers on Mars and it allows to expand the mission lifetimes, without the need of maintenance.

Based on the two laws of thermodynamics, the analysis of the exergy efficiency of solar energy conversion has been done successfully on Earth and it has been applied to Mars in this paper. The exergy efficiency of solar energy conversion can be divided in two terms: an electric component, dealing with the manufacture process and the technology; and a thermal component, which is determined by the interaction of the solar panel with its environment. The maximum electric efficiency obtained nowadays is about 45% with typical values of 15%. Regarding thermal exergy efficiency, the values obtained on Mars are almost zero and, on Earth, the calculations of the thermal efficiency are about 20–30% [16].

Looking at Eqs. (10) and (11) we have identified the atmospheric density as the parameter responsible of the low efficiency on the solar radiation conversion. Typical value of the Earth's atmospheric density is approximately 1.225 kg m^{-3}, whereas on Mars the typical values are about 0.020 kg m^{-3}, i.e., two orders of magnitude lower. The lack of atmospheric density is a critical factor on the analysis of thermal efficiencies on Mars, since the rest of the variables included in the equations have values of the same order of magnitude than on Earth.

The analysis on Earth gives values around 30% of efficiency in the thermal term, while on Mars the typical values are near zero. This implies that thermodynamical arguments do not determine the locations of the panels on Mars, and the choice should be done following those places where the irradiance is maximum, i.e., the equator. In order to increase the efficiency of the conversion, efforts should do in order to increase the electrical term, since the thermal part is extremely low to be considered.

The thermal power term should be improved in order to increase the thermal efficiency. The low density of the Martian atmosphere is responsible of the low thermal efficiency, but it might be counteracted increasing the thermal power. The thermal power is a linear function of the differences of temperatures between the ambient and cell and s the ambient temperature is fixed, it is necessary to maintain a low operating cell temperature to increase the efficiency of the transformation. In order to achieve those low temperatures, efforts should be focused in refrigerating systems optimized for the Martian environment.

In this paper, we have considered the simplest case of a flat solar panel on Mars. However, more efficient configurations and devices are nowadays available on Earth and its utilization could be used in the future on Mars for solar energy conversion, which could increase the values presented in this paper. Due to the lack of research on Martian solar exergy and the difficulty of the measurement of environmental parameters on Mars, we cannot compare our results with similar studies.

Other renewable source of energy used on Earth is wind power. The low density of the Martian atmosphere and the low wind speeds make the wind energy an inappropriate power source. The size of the structures needed to generate enough energy to maintain spacecrafts or human beings on Mars requires a capability to transport which do not have nowadays. Also, the construction should be done with materials supporting the dust interaction and the corrosion, since the presence of chlorine or other elements could damage the structures [47].

Acknowledgements

The first author wants to acknowledge the Luleå University of Technology in Kiruna, Sweden, for the scholarship award that partially funded this investigation.

References

[1] Grotzinger JP, Crisp J, Vasavada AR, Anderson RC, Baker CJ, Barry R, et al. Mars Science Laboratory mission and science investigation. Space Sci Rev 2012;170(1–4):5–56.
[2] Badescu V. Mars: prospective energy and material resources. 1st ed. Berlin: Springer; 2010.
[3] R. Evans, A proof that essergy is the only consistent measure of potential work, Doctoral Thesis, Dartmouth College.
[4] Rezac P, Metghalchi H. A brief note on the historical evolution and present state of exergy analysis. Int J Exergy 2000;1(4):426–7.
[5] Sahin A, Mokheimer E, Bahaidarah H, Antar M, Gandhidasan P, Ben-Mansour R, et al. Special issue: thermodynamic optimization, exergy analysis, and constructal design. Arab J Sci Eng Sect B Eng 2013;38(2):219.
[6] Petela R. Exergy of heat radiation. J Heat Transf 1964;86(2):187–92.
[7] Spanner D. Introduction to thermodynamics. New York: Academic Press; 1964.
[8] Landsberg P. A note on the thermodynamcis of energy conversion in plants. Photochem Photobiol 1977;26:572–3.
[9] Landsberg P, Tongue G. Thermodynamics of the conversion of diluted radiation. J Phys.A Math.Gen 1979;12:551–62.
[10] Jeter S. Maximum conversion efficiency for the utilization of direct solar radiation. Sol Energy 1981;26:231–6.
[11] Joshi A, Dincer I, Reddy B. Development of new solar exergy maps. Int J Energy Res 2009;33(8):709–18.
[12] Rose P. Entropy of radiation. Phys Rev 1954;96:555. http://dx.doi.org/10.1103/PhysRev.96.555.
[13] Ore A. Entropy of radiation. Phys Rev 1955;98:887–8. http://dx.doi.org/10.1103/PhysRev.98.887.
[14] Landsberg P, Tongue G. Thermodynamics energy conversion efficiencies. J Appl Phys 1980;51:R1–20.
[15] Pujol T, North G. Analytical investigation of the atmospheric radiation limits in semigray atmospheres in radiative equilibrium. Telus A 2003;55:328–37. http://dx.doi.org/10.1034/j.1600-0870.2003.00023.x.
[16] Le Corre O, Broc J, Dincer I. Energetic and exergetic assessment of solar and wind potentials in Europe. Int J Exergy 2013;13(2):175–200.
[17] Neri M, Luscietti D, Pilotelli M. Computing the exergy of solar radiation from real radiation data on the italian area. In: 12th joint European thermodynamics conference; 2013.
[18] Alta D, Ertekin C, Evrendilek F. Quantifying spatio-temporal dynamics of solar radiation exergy over Turkey. Renew Energy 2010:2821–8.
[19] Ranjan K, Kaushik S, Panwar N. Energy and exergy analyses of solar ponds in the Indian climatic conditions. Int J Exergy 2014;15(2):121–51.
[20] Dincer I, Rosen MA. Exergy: energy, environment and sustainable development. 1st ed. New York: Elsevier; 2007.
[21] Kalogirou SA, Karellas S, Badescu V, Braimakis K. Exergy analysis on solar thermal systems: a better understanding of their sustainability. Renew Energy 2016;85:1328–33. doi:http://dx.doi.org/10.1016/j.renene.2015.05.037.

[22] Hepbasli A, Alsuhaibani Z. Estimating and comparing the exergetic solar radiation values of various climate regions for solar energy utilization. Energy Sources, Part A Recovery, Util Environ Eff 2014;36(7):764–73.
[23] Soni SK, Pandey M, Bartaria VN. Hybrid ground coupled heat exchanger systems for space heating/cooling applications: a review. Renew Sustain Energy Rev 2016;60:724–38. doi:http://dx.doi.org/10.1016/j.rser.2016.01.125.
[24] Gómez-Elvira J, Armiens C, Castaner L, Domínguez M, Genzer M, Gómez F, et al. REMS: an environmental sensor suite for the Mars Science Laboratory rover. Space Sci Rev 2012;170(1–4):583–640.
[25] Conrath B, Pearl J, Smith M, Maguire W, Christensen P, Dason S, et al. Mars global surveyor thermal emission spectrometer (TES) observations: atmospheric temperatures during aerobraking and science phasing. J Geophys Res 2000;105(4):9509–15.
[26] Christensen PR, Bandfield JL, Hamilton VE, Ruff SW, Kieffer HH, Titus TN, et al. Mars Global Surveyor Thermal Emission Spectrometer experiment: investigation description and surface science results. J Geophys Res Planets 2001;106(E10):23823–71.
[27] Sark W v, Reich N, Muller B, Armbruster A, Kiefer K, Reise C. Review of PV performance ratio development. American Solar Energy Society, Boulder/Colo.: World Renew Energy Forum, WREF 2012;6:4795–800.
[28] Fraunhofer Institute for Solar Energy Systems, World record solar cell with 44.7% efficiency, ScienceDaily September.
[29] D. Rapp, Solar energy on Mars, QSS Group, Inc. in Affiliation with JPL JPL D-31342-vol. 1.
[30] Pollack JB, Haberle RM, Schaffer J, Lee H. Simulations of the general circulation of the Martian atmosphere. Polar processes. J Geophys Res 1990;95:1447–73.
[31] M. T. Lemmon, The Mars science laboratory optical depth record, Eighth international conference on Mars.
[32] Petela R. Engineering thermodynamics of thermal radiation: for solar power utilization. 1st ed. McGraw-Hill Professional; 2010.
[33] Planck M. The theory of heat radiation. 1st ed. Philadelphia: P. Blakiston's Son & Co.; 1913.
[34] Rant Z. Exergie, ein neues wort für technische arbeitsfähigkeit. Forschung Ing.-Wesens 1956;22:36–7.
[35] Bejan A. Unification of three different theories concerning the ideal conversion of enclosed radiation. J Sol Energy Eng 1987;109(1):46–51.
[36] Candau Y. On the exergy of radiation. Sol Energy 2003;75:241–7.
[37] Press W. Theoretical maximum for energy from direct and diffuse sunlight. Nature 1976;264:735.
[38] Parrot J. Theoretical upper limit to the conversion efficiency of solar energy. Sol Energy 1978;21:227.
[39] Skoplaki E, Boudouvis A, Palyvos J. A simple correlation for the operating temperature of photovoltaic modules of arbitrary mounting. Sol Energy Mater Sol Cells 2008;92(11):1393–402.
[40] Eckstein JH. Engineering thermodynamics of thermal radiation: for solar power utilization. 1st ed. University of Wisconsin-Madison; 1990.
[41] Delgado-Bonal A, Martín-Torres FJ. Solar cell temperature on Mars. Sol Energy 2015;118:74–9.
[42] Gómez-Elvira J, Armiens C, Carrasco I, Genzer M, Gómez G, Haberle R, et al. Curiosity's rover environmental monitoring station: the first 100 sols. J Geo Res Planets 2014;119(7):1680–8.
[43] Reiss D, Spiga A, Erkeling G. The horizontal motion of dust devils on mars derived from {CRISM} and ctx/hirise observations. Icarus 2014;227(0):8–20.
[44] Golding EW. The generation of electricity by wind power. 1st ed. London, England: E&F. N. Spon Ltd; 1955.
[45] Pedersen T, Petersen S, Paulsen U, Fabian O, Pedersen B, Velk P, et al. Recommendation for wind turbine power curve measurements to be used for type approval of wind turbines in relation to technical requirements for type approval and certification of wind turbines in denmark. Dan Energy Agency September 1992;(1).
[46] Ahmet Duran S, Dincer I, Rosen M. Thermodynamic analysis of wind energy. Int J Energy Res 2006;30:553–66.
[47] Martín-Torres FJ, Zorzano M-P, Valentín-Serrano P, Harri A-M, Genzer M, Kemppinen O, et al. Transient liquid water and water activity at Gale crater on Mars. Nat Geosci 2015;8:357–61.