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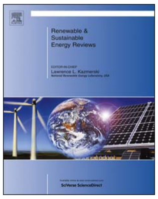

Occupational exposures to solar radiation in concentrated solar power systems: A general framework in central receiver systems

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ABSTRACT

Due to the growing motivation of countries to use renewable energy, instead of fossil fuels, for the production of electricity, the number of solar power plants had an increase in recent times. The sun as a renewable source is used by the Concentrated Solar Power systems (CSP) to achieve this goal. This process results in a considerable amount of concentrated solar radiation (visible light, infrared and ultraviolet radiation) inside and in the neighborhood of the installations. Some previous studies have addressed the possible risks for health of workers in environments where they perform activities in outdoors exposed to solar radiation. The overall purpose of this paper is to provide information about the environmental conditions in facilities using CSP technology, the effects of solar radiation in humans and the methods for the risk assessment in this type of facilities. Several standards including elements applicable to the field of occupational health in the central receiver area of solar power plants are also referred.

1. Introduction

The radiation, coming from the sun, is used as a renewable energy source in solar thermal power plants for the production of electricity. Like any other form of energy, the solar radiation has the potential to interact with biological systems [1,2].

Since, according to National Renewable Laboratory (NERL[1]) [3], solar thermal power plants have increased their number and capacity, there is an increased number of environments where the high levels of solar radiation represent a potential risks to human health. This paper has the main objective of analyzing the environmental conditions in solar facilities using central receiver technology in order to provide information that may improve the occupational health and safety in those locations.

1.1. Solar radiation and CSP technology

The solar radiation passing through the atmosphere is composed by three types of non-ionizing radiation (NIR), namely ultraviolet (UV), visible light (VL), and infrared (IR) radiation, and all of them are classified by its wavelength within the solar spectrum [Fig. 1].

Nearly half of the solar radiation can be perceived through the eyes and the rest of it cannot be perceived by any of the human senses unless the source has a high intensity so it can be perceived by feeling heat. The radiant heat (thermal radiation), known as infrared radiation, is emitted by all objects with temperature above zero. IR radiation conforms almost half of the solar radiation, and it is subdivided in IR-A, IR-B and the IR-C through the solar spectrum. Besides IR radiation in the solar spectrum, the VL is the part of it that can be perceived with the eyes. The UV is a form of optical radiation of shorter wavelengths and photons (particles of radiation) more energetic than VL; subdivided into UV-A, UV-B and UV-C. Solar radiation classification differs somehow depending on the involved discipline [Fig. 2]. For example, in the area of environmental and dermatological photo-biology, UV radiation is usually defined as UV-A from 400 to 320 nm, UV-B from 320 to 290 nm and UV-C from 290 to 200 nm [1,2,4–7].

Brauer [4] considers the part of UV that falls on the range between 200 and the 315 nm as a concern in order to ensure human health and safety, while Kwan-Hoong [2] believes that the biggest risks to the public are the ones coming from visible light and ultraviolet radiation or, in other words, natural light exposures. Natural light is present in solar thermal power plants in a daily basis, and, due to the countries' motivation of using renewable energy sources for electricity production instead of fossil fuels the risk of exposure of the workers to light radiation is expected to have a significant increase.

One of the several types of solar thermal technology is based on the concept of the concentration of sunrays, known as the concentrated solar power (CSP) system. It uses the solar radiation as a renewable source for the electricity production through a thermodynamic cycle [8,9].

In 2013, Behar et al. [10] recognized that, among all the CSP technologies available in the late years, the one that uses central receiver system (CRS) is the type of technology moving to the forefront, giving it a chance to become the technology of choice.

Basically these systems concentrate the sunrays on the receiver

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[1] See a list of abbreviations and symbols in Appendix A.

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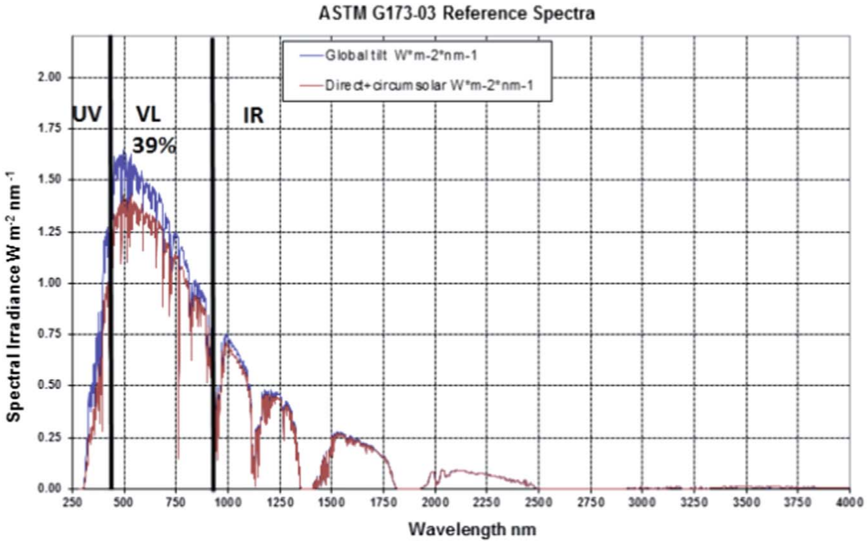
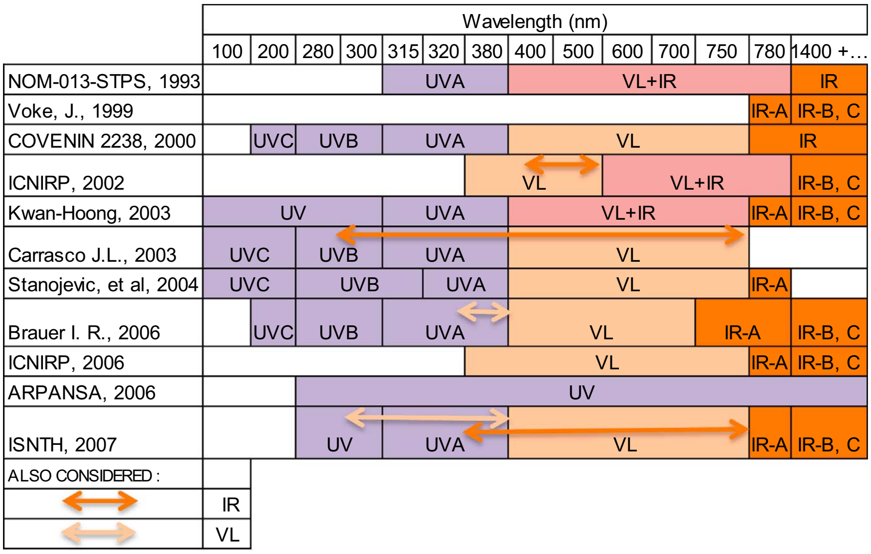


Fig. 1. Solar spectrum based on ASTMG173–03 (ASTMG173-03 represents the standard terrestrial solar spectral irradiance distribution developed by American Society for Testing and Materials (ASTM)). Own elaboration.



	Wavelength (nm)													
	100	200	280	300	315	320	380	400	500	600	700	750	780	1400 +…
NOM-013-STPS, 1993					UVA			VL+IR						IR
Voke, J., 1999													IR-A	IR-B, C
COVENIN 2238, 2000		UVC	UVB		UVA			VL					IR	
ICNIRP, 2002							VL			VL+IR				IR-B, C
Kwan-Hoong, 2003	UV				UVA			VL+IR					IR-A	IR-B, C
Carrasco J.L., 2003	UVC		UVB		UVA			VL						
Stanojevic, et al, 2004	UVC		UVB			UVA		VL					IR-A	
Brauer I. R., 2006		UVC	UVB		UVA			VL				IR-A		IR-B, C
ICNIRP, 2006							VL						IR-A	IR-B, C
ARPANSA, 2006			UV											
ISNTH, 2007			UV		UVA			VL					IR-A	IR-B, C
ALSO CONSIDERED :														
⟷	IR													
⟷	VL													

Fig. 2. Wavelength classifications. Literature adaptation ([2] Kwan-Hoong, 2003, [4] Brauer, 2006, [5] Carrasco, 2003, [19] Stanojević, et al., 2004, [32] Voke, 1999, [33] Segura and Calvo, 2007, [47] ICNIRP, 2002, [79] ACGIH, 1993, [83] CEN, 2004, [84] COVENIN, 2238: 2000, [85] ARPANSA, 2006).

by reflecting the sun light through heliostats' surfaces (mirrors) [11]. The receiver absorbs the concentrated solar energy and transfers it to a circulating fluid. The heated fluid is pumped into storage tanks and passed across a heat-exchanger, where steam is produced. This steam is used in a turbine connected to a generator in order to produce electricity [8,9,12]. The heliostat's surface is designed to focus the beams on the receiver where the reflected light will be scattered on a level that increases proportionally to the distance between the heliostat and the focal point.

These reflections can be classified in different human-interacting situations according to Franck et al. [13]: the reflection aimed at the sky (potential risk for pilots), non-concentrated reflection from one single heliostat (potential risk for a person standing in front of the mirror), concentrated solar radiation from the heliostats field (potential risk for the workers located in the solar tower), and solar field and beyond (potential risks for people outside the heliostats field although nearby, i.e. roads, neighbors and pedestrians) [14].

Other scenarios can be also added according to Ho et al. [15], e.g., the diffuse radiation from the receiver, the reflection from the mirrors when they are moving from the standby mode or stowed position and when they are not oriented towards the receiver.

In order to take full advantage of solar energy, the CRS has to be submitted to regular heliostats cleaning and maintenance because those activities will allow the maximum reflectivity from the heliostats surface to achieve the desired productivity levels [16,17]. The cleaning activities can be rather accomplished by a cleaning system based on wet brushing (robot) [16] or/ and by manual activities (when it might be required [18]. Special cleaning care is required in cases with the presence of some environmental agents, such as chemical compounds attached to the heliostat surface, dust, smog and/or air contaminants.

On the other hand, Hamilton [8] provided information about solar jobs and classified some of the duties as repetitive, physically demanding, and sometimes developed under inclement weather conditions. The situation is more evident especially for those workers in charge of the control and operation of pump manifold systems and also the ones in charge of the installation, maintenance and reparation of the pipe systems.

The CRS facilities are usually located in sunny environments with a high solar ultraviolet index [13] and solar radiation has the potential to has impact in biological systems [1,2]. Locations with these characteristics may represent an indirect drawback because working places under that kind of environmental conditions seem to allow possible scenarios of potential risks for human health. Therefore, it may be necessary to analyze the environmental conditions in order to ensure the occupational health and safety in future facilities.

1.2. Health impacts

The sun, considered as the principal source of visible light, ultraviolet and infrared radiation, has the potential to transmit its irradiance (energy coming from a source) to the surrounding bodies. When a body surface is exposed to such incident irradiance, scatters a part of it and absorbs the other portion in the form of photons. The absorbed fraction induces cellular reactions causing alterations (effects) directly or indirectly in the biological system, which is susceptible to produce physiological, biochemical or behavioral changes, resulting, from that process, skin impacts (erythema and burns) and several types of damage to the eyes [2,4,5,19].

According to Toet et al. [20] some of those effects can be classified as reversible when the effect is physiologically healed with time, even though those situations can lead to secondary effects. In the opposite way, long-term hazards that cannot be healed with time because the occurred alteration is a permanent damage lead Toet et al. [20] to classify them as irreversible effects. Usually long-term hazards are related with UV chronic exposures, where skin cancer and skin aging (photo-aging) are the main examples [21]. According to Knave [1] and Brauer [4] the relationship between the dose (determined by the duration of the exposure and the amount of radiation) and the response to human skin carcinogenesis has not been clearly established yet, but the individuals with white skin and those individuals with burns history, especially if these burns were produced in a young skin, are more likely to develop skin cancer, comparatively to those with occupations requiring extensive outdoor work and those who live in sunny regions.

In Cuba, Fernández et al. [22] conducted a study aiming to identify different occupational factors associated with skin cancer. The study reaffirmed that skin cancer has a directly relation with heat, sunlight and non-ionizing radiations, in combination with some chemicals and other factors such as people with fair skin, old age people, the location of the exposure and the biological characteristics of the individual.

When a surface of a body is exposed to solar radiation, a temperature rise is noticed. In fact, when the incident irradiance reaches the body surface, an increment on the body's temperature is produced, where an interchange of thermal radiation (present in the IR, VL, and a portion of UV radiation) occurs. The initial physiological response of the human body starts with the action of sweating. If the heat persists, it leads into abundant sweating susceptible to induce dehydration and the rise of the deep-body temperature, ending the process in a whole system collapse. The collapse is cause by the absence of thermal equilibrium or heat balance between the body and the environment [7,23].

The OSHA (Occupational Safety and Health Administration) defined two health effects in consequence of exposures to hot environments, namely heat stroke and heat exhaustion [24]. According to Parsons [23] there are also behavioral disorders that can negatively influence the performance capacity of the workers due to the discomfort and psychological stress, produced by a hormonal imbalance, which leads to a considerably decrease of their productivity.

However, all biological changes depend on a multitude of different factors such as radiation dose, intensity of the source, time and duration of exposure, power of the radiant beam, characteristics of the source emission, environmental conditions (clouds, air pollution, air humidity, etc.), type of work activities, biological conditions of the body (e.g. the type of skin), and the capacity of absorption of different tissues. It also depends on the wavelength because in the electromagnetic spectrum of solar radiation, some wavelengths are more energetic than others. It may be also hard to know whether people are sufficiently sensitive to react physiologically to subtle changes in the spectral content of radiation [2,4,6,19,21].

With the previous health impacts information, the classification of the effects in human health seems to be a complex topic. Therefore, hazards are summarized in Table B1, Appendix B (pp. 39), in order to identify the potential health effects, biological system affected area, wavelength, primary, secondary and side-effects.

1.3. CRS assessments of environmental conditions: previous studies

The first risk assessments associated with environmental conditions in a solar central receiver facility were made by Young [25] and Brumleve [26] and took place on the experimental installations of Sandia National laboratories in Albuquerque, New Mexico. Brumleve [26] developed analytical models to assess the intensity of the light, both in single and multiple heliostats, and the dangerous ranges of multiple rays. His results showed that the irradiance of a single heliostat exceeds the safety limits within a short focal distance (up to 40 m), but the safe limits for damage in the retina were never exceeded in heliostats with focal lengths of more than 270 m.

In 2009, Ho et al. [27] showed in their work a summary of the previous analysis of the glint and glare effects, and the possible optical damage. A review of physiology and optics associated with radiation was included as well. The study resumes safety limit values and regulations from the literature to define the glint and glare potential risks. Subsequently it is also suggested a series of safety metrics ranges for the eye hazards prevention.

One year later, Franck et al. [13], explored the operation and design aspects of a central tower installation in Israel (a facility with 1600 heliostats approximately in operation since 2008). The analyzed potential risks, for skin and eyes, were related with the exposure to brightness of the reflected sunlight from the heliostats and the glow of the receiver.

In 2011, two studies [15,28] took place at the National Solar Thermal Test Facility; those studies basically corroborated the situation exposed in Ho et al. [27] in 2009. Ho, in collaboration with Ghanbari and Diver [15], analyzed the brightness of the receiver in digital photographs. The study allowed the evaluation of ocular impacts by the quantification of the irradiance flux in each pixel of the photographs. The study revealed that heliostats that were placed in a standby mode provide a strong brightness and it could be seen at a distance of more than one mile away (1700 m). This result was a clearly evidenced that the brightness was enough to cause a temporary impact after seeing the source directly; the effect was called “after-image effect”.

The studies about the after-image effect started in 1969 with

Table 1
Number of solar workers by sector.
Source:Reproduced from [49].

	2010	2011	2012	2013	2014	Projected 2015
Installation	43,934	48,656	57,177	69,658	97,031	118,942
Manufacturing	24,916	37,941	29,742	29,851	32,490	37,194
Sales & Distribution	11,744	13,000	16,005	19,771	20,185	25,480
Project Developers	no category	no category	7988	12,169	15,112	18,004
All other	12,908	5548	8105	11,248	8969	10,440
Total	93,502	105,145	119,016	142,698	173,807	210,060

Saur et al. [29]. Recently, in 2013, Toet et al. [20] defined the after-image effect as a blind spot in the visual field which persists from seconds to a few minutes after the light is no longer in the visual perimeter.

Due to the significance brightness from heliostat field and the induced phenomena occurrence, Samaniego et al. [30] evaluated the eye hazards due to solar radiation exposure in a CRS experimental facility in Mexico. Basically the levels of solar radiation were estimated with the “SOLTRACE software”, and compared the results with the maximum permissible limits showed in previous studies. The two analyzed cases, the actions of looking directly at the heliostat's surface and looking directly at the receiver's surface, showed that, in the range of 100 m, retinal injuries and after-image effect could be noticed in people.

In 2014, Ho et al. [31] made a study requested by the solar power plant Ivanpah located in the United States, due to the reports submitted by pilots and air traffic controllers about the glare originated from this facility. The fact drove to the evaluation of the glare, in order to understand the causes and health impacts. Once they quantified the irradiance in the facility and identified the potential ocular impacts of the glare source, mitigation measures were taken. The results showed the intense glare caused by the heliostats' surfaces in standby mode (when deviated to the side of the receiver), and the potential to cause an after-image effect (up to a distance of 10 km). In the case of the receiver's surface, the glare had a low potential to cause the same effect.

2. Green jobs hazards

The European Occupational Safety and Health Agency (EU-OSHA) [43] provides a full description of possible future insides in green jobs. The Bureau of Labor Statistics (BLS) defines the term "green job" as those jobs in which workers' duties involve making their establishment's production processes using natural resources [44]. According to the OSHA [24] in the United States of America (USA) the green jobs hazards, in solar energy workers industry, are mostly related with dehydration, heat stroke, heat exhaustion and, in extreme cases, may cause death.

In 2014, Xiang et al. [45] provided information about outdoor and indoor workers. From 43 reviewed studies, 44% of all of them were dealing with outdoor environments, 23% of all of them were carried out in America and only 7% in Europe. The results showed that in 90% of the cases, the individuals who work in outdoors presented discomfort due to the heat strain sensation; even though it is classified as no pathological effect, it can affect the physical and mental well-being of a person and should be considered a potential health hazard as well [45–47].

The Solar Foundation (TSF) [48] conducted a research based on the definition of “solar worker” (employee who spends at least 50% of all his work time supporting solar-related activities). It was found that 90.7% (almost 130,000 workers) of those who are called as a solar workers actually spend 100% of their time supporting solar activities.

The EU-OSHA [43], in order to inform policy makers, governments, trade unions and green industry employers, has defined different risk scenarios that might be present in the future renewable technologies appliances in Europe. The final report, which is the result of 26 interviews, summarizes nine technologies involving the occupational health and safety as:

- Wind energy,
- Green construction and building retrofitting,
- Bio-energy,
- Waste management and recycling,
- Green transport, green manufacturing,
- Robotics and automation,
- Batteries and energy storage,
- Domestic and small-scale renewable energy
- Energy transmission and distribution

Even though the solar energy production at industrial scale was not discussed, the fast development of new technologies for green energy production may surely impact in jobs growth [43].

In the annual solar jobs census in the United States of America, it was estimated 93,502 workers in the solar industry in the year of 2010; number that lately increased 53% in 2013 [48,49]. In November of 2014, the number increased 21.8% (173,807 solar workers) within 12 months, what means an increment of 86% since they started to make the solar jobs census in 2010. The projected number of solar workers for the year 2015 is around 210,060 workers [Table 1]. It is also projected [Fig. 4] the number of workers by working area in solar industry: installation, manufacturing, sales and distribution, project, among others, where the area of installation is on the top of the priorities list [49]. The workers in the installation sector, who spend at least 50% of their time on solar-related activities, are projected as 118,942 workers for late 2015 [Fig. 3].

Jobs related to solar power will increase in number as a consequence of the solar power industry growth, but those projections can be affected by the global competition, renewable energy targets, regulatory policies and other factors, such as economy stability [48]. E.g., Spain, once defined as the pioneer of renewables by International Renewable International Agency (IRENA) [50], had increased the number of concentrated solar power jobs until 2011 in spite of the crisis, but in 2012 around 6000 jobs were lost.

In addition, ABENGOA SOLAR [51], dedicated to the implementation of solar thermal facilities, in its 2013 annual report published that its employment index decreased from 20.9% (2012) to 3.4% (2013), in one year. Even though the loss of jobs in 2012, the facility Gema Solar (with a capacity of 19.9 MW and 2650

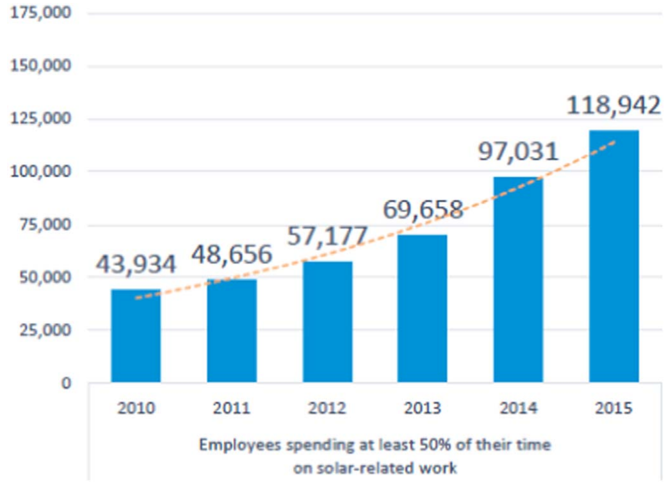


Fig. 3. Solar installation employment growth, 2010–2015 projection. Taken from [49].

heliostats) generated 1800 jobs during the construction period and 50 jobs for the operation phase [52].

United States, as the second worldwide country in concentrating solar thermal power capacity, reported 2600 workers for the construction and 86 jobs for the operation and maintenance activities of the CSP IVANPAH plant (377 MW of capacity and 173,500 heliostats). Meanwhile, in South Africa, KHI Solar (4120 heliostats and 50 MW of capacity) reported a total of 630 jobs in the same work areas [3,51,53].

Besides the solar industry workforce increments, the 2015 renewable global status report confirmed an increment in concentrating solar power capacity between the years of 2010 and 2013 [Fig. 4] [54].

Governments are increasingly aware of renewable energy's potential role in improving national development and with the markets becoming every day more global, renewables evolution has surpassed all expectations. TSF affirms that solar industry continues to exceed growth expectations in a rate nearly 20 times faster than the overall economy. Besides that, the global installed capacity and production also have increase substantially generating new jobs where a wider population faces new risks over shorter timescales [43,48,54].

3. Methods for the environmental conditions assessment

CRS technology facilities are usually located in sunny places with high ultraviolet index and the contributors of the ultraviolet index are also the reflected solar radiation from mirrors and the receiver. The burn times (level of burning under unprotected sun exposure) have been used as safe level limits of sun exposure which imply the concept of acceptable extending exposures; and sometimes workers expose themselves to those environmental conditions with a lower protection. The over goal, instead, is to avoid sunburns and cumulative exposure of UV radiation that can cause, in the future, cancer, damage in the eyes and immune system. Even though, the exposure effects on human health depend on the amount and type of radiation and, therefore, the application of preventive methods should be taken into consideration [13,55,56].

3.1. Skin

The skin exposure factor (F_{es}) is an indicator used for the assessment of the impact of the environmental conditions on skin [36,56]. F_{SE} is the result of the product of six factors (f_n) related with the environmental conditions of a particular location, and its equation is defined by [13]:

$$\mathbf{F_{es}} = f_1{*}f_2{*}f_3{*}f_4{*}f_5{*}f_6 \quad \text{(see Appendix C, pp. 40)} \tag{1}$$

where each of the f_n factors is related to:

f_1- geographical latitude and season (spring & summer; autumn and spring),
f_2- cloud cover (clear sky=1, partial cloud sky=0.7, overcast sky=0.2),
f_3- duration of the exposure (all day=1, one or two hours in midday=0.5, early morning or late afternoon=0.2),
f_4- ground reflectance (fresh snow=1.8, dry sand=1.02, all the others=1),
f_5- clothing (unprotected=1, arms and legs exposed=0.5, hands and face exposed=0.02),
f_6- shade (total shade=0, high density housing=0.02, low density housing=0.3, no shade=1).

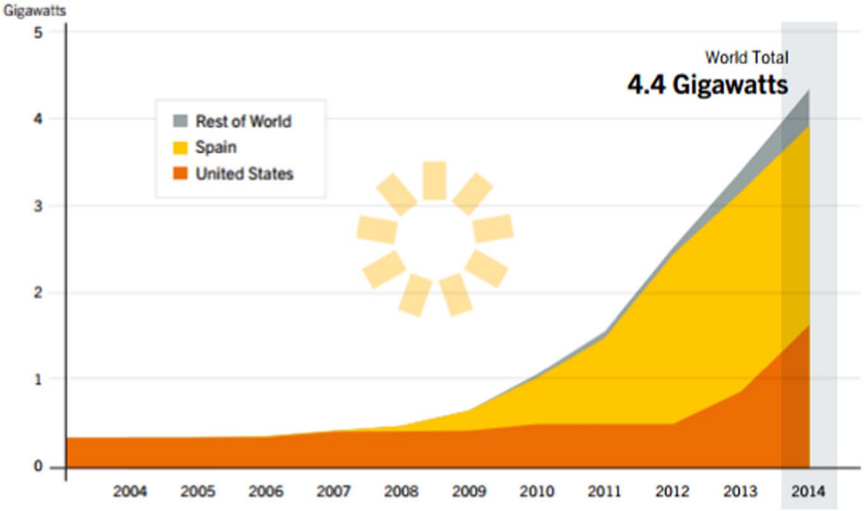


Fig. 4. Concentrating solar thermal global power capacity. Taken from [54].

According to the International Commission on Non-Ionizing Radiation Protection (ICNIRP), F_{SE} should not exceed 30 J/m^2 within 8 h (working shift); both in eyes and skin for UVR exposures. In terms of acute skin effects from solar exposure, it is equivalent to approximately 1.0–1.3 SED (Standard Erythema Dose), i.e., approximately one-half of an MED (Minimal Erythema Dose) for fair skin [13,36].

SED, defined as the amount of UVR reaching the skin surface, differs from MED, which depends on the skin type defined by the Fitzpatrick skin pigmentation scale [55]. MED is based on the required UVR dose to produce a noticeable impact (erythema) on the human skin. The unitary value of SED is equivalent to an erythemal effective radiant exposure of 100 J/m^2. MED is expressed as approximately 2 SED or 200 J/m^2 of an individual person [37,55–58]. This indicates the minimum dose of erythemal radiation that produces a notorious impact in the skin 24 h after being irradiated [59]. In other words, MED may represent a sun burn limit.

The suggested safe SED, per day, in an experimental solar central receiver institution is around 200 J/m^2 a day (2 SED/day), according to Azizi and Kudish (2008) (as cited in [13]).

In 2013, Wolska [46] proposed a (F_{SE}) modified method for the skin hazard assessment due to UV radiation exposure. It consisted in substituting the Solar UV-index (I_{UV}) from a particular day and geographical place (maximum I_{UV} value to clear sky conditions) with the geographical latitude and season factor. Considering the most common clothing of outdoor workers in that location, that author introduced additional values of the clothing factor in the Eq. (1). Three additional values for clothing (0.40 for arms, head and neck exposed, 0.35 for arms and neck exposed, and 0.7 for head and neck exposed) were considered, plus the cloudiness condition of 0.5.

The SED, per work shift (8 h), was defined as 10 SED (1000 J/m^2 per 8 h), which means that the dose rate, in a period of 8 h, should not exceed 1.25 SED in one hour (1.25 SED/h). The dose rate was suggested per hour because the duration and time of work activities may vary within the work shift [46].

The **F_{es}** is applied in the situation of facing the risk with no protective measures and the corrected Skin exposure factor (**F_{es}***) takes into account the use of protective measures (see Appendix C, pp. 42), were calculated by:

$$\mathbf{F_{es}} = I_{UV} * F_2 * F_4; \tag{2}$$

F_2 = cloud cover; F_4 = ground reflectance.
$F_{es} \leq 1$ low risk, no additional preventive measures needed.
$F_{es} < 1$ preventive measures are necessary

Then, the correction of the F_{es} factor was:

$$\mathbf{F_{es}}^* = (F_{es})*(F_3)*(F_5)*(F_6) \tag{3}$$

F_3 = duration of the exposure; F_5 = clothing factor; F_6 = shade factor.

All the ambient UV radiation descriptors, based on an erythemal response function, have their advantages and disadvantages [55]. The decision of using one of them has to be based on the overall objective and criteria used for the risk assessment. The advantage of using the I_{UV}, as a preventing method, is that it can be determined by data taken from weather stations in public access sources such as internet. The limiting condition is when the data are used as a mean because sometimes the weather could differ from the forecast and so will do the UV- index. Also, it does not take into account individual factors (posture, clothing and exposure time) [57]. MED, in other hand, cannot be used in populations with different types of skins. This fact limits the user to apply the assessment method to each individual instead of a group [55]. In the case of the F_{SE} factor, real measures are not taken into account, so the procedure has a lower accuracy. In particular cases, and when the situations demand it, applying a methodology based on empirical models instead of estimating models is highly suggested [55,57].

- **Skin cancer**

People who spend working-periods outside are exposing themselves to solar radiation in those days. Cumulative exposures to UV radiation are responsible for some forms of melanoma (MM) which is one of the three types of cancer related with chronic exposures of outdoor workers. The other two are Basal Cell Cancer (BCC) and Squamous Cell Cancer (SCC) [36,37,39]. On other hand, Christophers [60] believes that sunlight exposure cannot be the cause of Melanoma, but it is a predominant factor for the development of SCC and a less significant factor for the appearance of BCC. Even though the recognition of skin cancer as occupational hazard remains scarce, it is still the most frequent carcinogenic agent in many countries [39].

In 2014, Blazejczyk et al. [39] developed a method in order to estimate the incidence of SCC, where basically they assessed the anatomical exposures to solar UV with the Sim UVEx (Simulating UV Exposure). The model predicts the dose and the anatomical distribution of radiation received on the basis of ground irradiance and morphological data. It allows taking into account parameters such as body inclination, orientation to the sun and shading body parts. It also requires some input parameters such as the direct irradiance, diffuse irradiance, ground reflected irradiance and sun position (azimuth and zenith) [39,61].

The ambient UV data was both simulated and measured with radiometers. Then the estimation of SCC risk was expressed as a function of age and cumulative exposure UV dose by (see Appendix C, pp. 42):

$$SCC_{risk} = \text{Risk}\ \alpha\ (\text{age})^{\alpha} \times (UV_{tot})^{\beta} \tag{4}$$

where: α=age dependent factor, β=biological amplification factor, and UV_{tot}=cumulative UV exposure dose received.

The cumulative UV dose is expressed as a sum of the exposures during the work (UV_{occ}) and lunch (UV_{lunch}) during $\boldsymbol{n}$ years of occupational activity and recreational (UV_{recr}) time from 0 to $\boldsymbol{n}$:

$$\sum\nolimits_0^n UV_{tot} = \sum\nolimits_{n1}^{n2} (UV_{occ} + UV_{lunch}) + \sum\nolimits_0^n UV_{recr} \tag{5}$$

The UV_{occ}, and UV_{lunch} were obtained from SimUVEx model, and UV_{recr}, from a survey.

In similitude with other methods, some factors had not been taken into account such as the access to shaded spots, indoor working periods, taking lunch outside, absences at work or clothing, and, besides that, the model assumes a constant for the annual exposure without any variation (long periods outside, no protective clothing and no shade) so the values should be considered upper values [39,61].

3.2. Ocular

The eye is significantly more sensitive to solar radiation than the skin; therefore the damage mechanisms are different in the two of them and should be assessed separately. The eye is protected against the bright light by natural responses that commonly are the action of blinking or the action of looking to other side instead the bright source, ending this process in a momentary exposure. Even if the workers are exposed to lower momentary intensities, the cumulative exposures might cause an acute damage [13,62,63].

Ho et al. [15,27] proposed a short-term exposure parameter in order to assess the bright light sources in CSP installations. In the study two variables were defined as necessary for the evaluation of the impact of solar radiation in the eyes: retinal irradiance (E_r), which is the power of the solar radiation that strikes a surface, and the subtended angle of the glare source (ω).

$$\omega = d_s/r \tag{6}$$

where: d_s=source size; r=distance between the eye and the source.

Since the radiation in the frontal plane of the cornea E_C (W/m^2) has to be known, the estimation of it can be either measured with a radiometer or simulated by a software, e.g., SolTRACE [30]. Then, the E_r (retinal irradiance) can be calculated by the total power that enters in the pupil and the area of the retinal image:

$$E_r = E_c\left(\frac{dp^2}{dr^2}\right)\tau \tag{7}$$

where: d_p=daylight adjusted pupil diameter (~2 mm) [15], and d_r=$f\omega$ is the product of focal length of the eye (0.017) and the subtended angle [64], and τ=transmission coefficient (~0.5) [15].

The relation of the subtended angle and the retinal irradiance with the potential risk to the eye resides in the moment that ω increases and the safe threshold for E_r decreases proportionally. In other words, the delivery of power into the retina occurs in large amount and permanent eye damage might occur. It can be represented by $E_{r,\ burn}$ (burn in the retina, in W/cm^2) and, according to Brumleve [26], as cited in [15,50], the threshold should be delimited by:

$$E_{r,burn} = \frac{0.118}{\omega}\ for\ \omega<0.118\ rad \tag{8}$$

$E_{r,burn}$=1 $for\ \omega\geq0.118\ rad$; where ω is the subtended angle (rad).

As the burns in the retina, the temporary blindness caused by a flash (after-image effect) also depends on the size of the subtended angle of the source, but differs on the severity of impact. Brumleve [26] and Ho [27], affirm that the size of the after-Image and the impact would be lower for small angles. The potential threshold of after- image ($E_{r,\ flash}$) (W/cm^2) can be calculated in the following way:

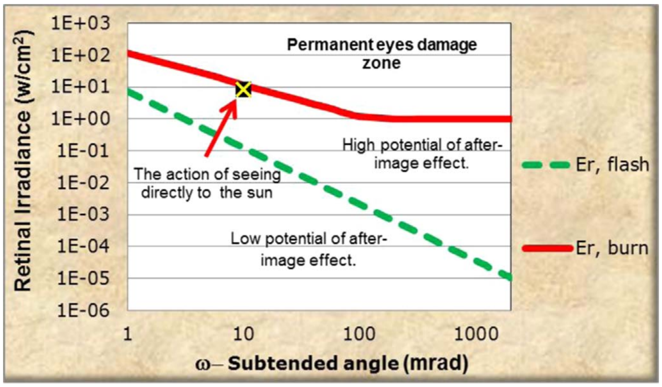


Fig. 5. Potential effects represented in function of the subtended angle. Reproduced from [15].

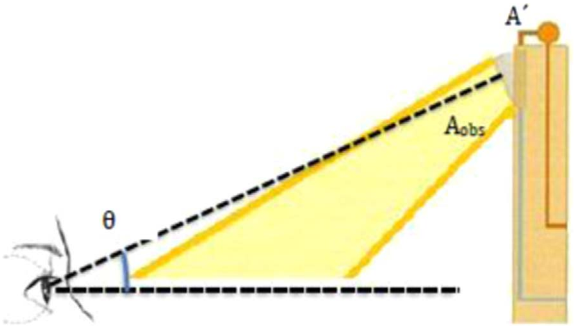


Fig. 6. Observer respect to the receiver. Own elaboration.

$$E_{r,flash} = \frac{3.59\times10^{-5}}{\omega^{1.77}} \tag{9}$$

Once the values of E_r are calculated, they can be compared with the security metrics provided by Ho et al. [15] in the work "Methodology to Assess Potential Glint and Glare Hazards from Concentrating Solar Power Plants". Fig. 5, resumes the potential effects in the eye of a short-term exposure. Three regions of potential effects were defined: the risk of permanent damage to the eyes or retinal burn in 0.15 s (typical average time of blink response), potential for a temporary after-Image effect (flash blindness), and low potential to produce after-image effect.

It is important to be noticed the fact that the quantified metrics and retinal irradiance estimations do not consider all the factors and situations, e.g. the atmospheric attenuation, the protective effect of wearing sun glasses, human factors and behaviors, and also the effect of multiple beams from an adjacent receiver [15].

The action of seeing the reflection from the receiver can be modeled as a diffuse source because it is designed to absorb the concentrated solar radiation coming from the heliostats field [15]. In 2012, Samaniego et al. [30] suggested a way to evaluate the reflected irradiance coming from diffuse sources based on the methodology proposed by Ho et al. [15]. The angular size of the source is determined by the effective area reflected on the receiver's surface that is seen by the observer [Fig. 6]. The effective area seen by the observer (A_{obs}) depends on the total illuminated area, on the receiver's surface and on the angle of the observer with respect to the receiver. At the same time, it depends on the tower height and distance.

$$A_{\text{obs}} = A'\cos\theta \tag{10}$$

where:

1. A_{obs}=Area seen by the observer
2. A'=Area of the reflecting surface

Once the total illuminated area is known, the reflected irradiance (E_{ref}) can be calculated (Eq. 11) by multiplying it by the reflection coefficient (ρ), which varies from 0.8 to 0.2.

$$E_{ref} = \rho E' \tag{11}$$

However, there is a difference between the total reflected radiation that is seen by the observer and the total amount of radiation just outside the cornea of the eye. The main reason is the distance and the angle in which the observer is located in respect to the receiver. The irradiance outside the cornea (E_c, in W/cm^2) is defined by:

$$E_c = E_{ref}A'\frac{X_{obs}}{(Z_{obs}^2 + X_{obs}^2)^{\frac{3}{2}}} \tag{12}$$

On the other hand, the energy (per cm^2) that enters through the pupil (E_r) is equal to the ratio of the energy that is outside the cornea; the area of the pupil for a determined distance (location of the observer) over the area seen by the observer, with a transmission coefficient of $\tau = 0.5$ and a focal length of the eye of $f = 0.017$ m.

$$E_r = \frac{E_c A_p \tau r_{obs}^2}{A_{obs} f^2} \tag{13}$$

The E_r calculation refers to the amount of radiation on the retina produced by a single heliostat. Therefore, the amount of radiation that reaches the retina by $\boldsymbol{n}$ heliostats is determined by an equivalent area for an equivalent irradiance.

$$A_{\text{equiv}} = \sum_{i=1}^{n} \frac{A'_{\text{n}}E'_{\text{n}}}{E'_{\text{n}}} \tag{14}$$

$$E_{\text{equiv}} = \sum_{i=1}^{n} E'_{\text{n}} \tag{15}$$

where: A_n and E_n are the area and irradiance for the **n** heliostats.

3.3. Thermal comfort and heat stress

In 2009, Parsons [23] pointed out that one person in thermal comfort needs to be in heat balance, which basically refers to a thermal neutrality state. This state occurs in the moment in which the heat gains are equal to the heat losses. In other words, a constant heat-exchange between the body and the environment is required to achieve this equilibrium [65–67].

In the equation of heat balance is defined by [68,69]:

$$\text{M} - \text{W} = (\text{C} + \text{R} + \text{E}_{\text{sk}}) + (\text{C}_{\text{res}} + \text{E}_{\text{res}}) + \text{S}_{\text{sk}} + \text{S}_{\text{C}} \tag{16}$$

where: M is the rate of metabolic heat production (W m^{-2}), W is the rate of mechanical work (W m^{-2}), C is the perceptible heat loss from skin by convection (W m^{-2}), R is the perceptible heat loss from skin by radiation (W m^{-2}), Esk is the rate of total evaporative heat loss from skin (W m^{-2}), Cres is the rate of convective heat loss from respiration (W m^{-2}), Hres is the rate of evaporative heat loss from respiration (W m^{-2}), Ssk is the rate of heat storage in the skin (W m^{-2}), Esk is the rate of heat storage in the core (W m^{-2}).

The risk of an organism overheating is an effect of this heat exchange process according to Fiala et al. (as cited in [40]). In hot conditions heat balance is mainly regulated by an increase in sweat evaporation from the body. In some conditions the excess of sweating can lead to dehydration. The physiological regulation of the body temperature can be insufficient to maintain thermal equilibrium leading to the increase of the body temperature, which might induce a collapse, heat stroke and/ or dead [24,67]. Besides, the discomfort and heat stress reduce workers' productivity [70].

In practical applications of human heat balance, the radiant fluxes play an important role, being: (1) solar radiation or short-wave radiation with wavelength of 0.3–0.4 μm divided in UV, VL and IR, and (2) thermal radiation or long-wave radiation (terrestrial radiation) with a wavelength between 4.1 and 50 μm. The radiant fluxes differ in description within the literature [66,72] which established that the solar radiation received as ~0.3–4 μm from VL and IR and the terrestrial radiation around ~4–100 μm. Also the radiant fluxes vary in space and time due to the dynamic behavior of the meteorological variables and the space-depending properties of irradiant surfaces in the surroundings [73].

The equation of the net radiation absorbed by a person is defined by [72]:

$$\text{Q} = \text{R} + \text{L} \tag{17}$$

where: L is the net long-wave radiation in a person and R is the short-wave radiation.

Based on the components of the human radiant energy budget presented by Jendritzky et al. [72], the short-wave radiant fluxes required for the calculation are: direct solar radiation, diffuse solar radiation, reflected solar radiation from the ground, long-wave fluxes (atmospheric radiation from the open sky and radiation from solid surface in surroundings) [66,74].

In the assessment of the influence of thermal environment conditions on the human body, there are several parameters or factors that should be measured or estimated, e.g., the air temperature, radiant temperature, humidity, air velocity, metabolic rate and clothing insulation [68]. The effects of all these factors are considered in thermal environment indices used as the basis of risk management programs with the objective of avoiding the occurrence of unacceptable levels of heat stress in people [23,65,75].

The precise estimation of the total absorbed radiation by a human body in an outdoor environment seems to be a very complex process, due to the interactions between the radiant fluxes in the sky and ground hemispheres, and the human body factors [66]. There exist around 40 indices for the assessment of the thermal comfort and heat stress listed by Epstein and Moran [65]. These indices are divided into three groups: (1) rational indices, (2) empirical indices, and (3) direct indices based on the measurement of environmental variables. The third group is more friendly and daily applicable in workplaces than the other two groups. The first two groups require many factors for their calculation and they are considered comprehensive groups, but they have their own difficulty. It resides in that there is no practical way to record invasive measurements of too many variables [65,76].

It can be said that the creation of a universal heat stress index is quite difficult, due to the complexity of the interactions between parameters, the number of the parameters and variability of location and time in the assessment process [65]. Furthermore, there are some considerations in the use of any index, e.g., the wet-bulb globe temperature (WBGT) requires specific measurements which are quite difficult to perform for long periods of time [65,76]. In the case of the Predicted Mean Vote (PMV), it cannot be applied in arid climates (as well as the Temperature Humidity Index), or places with extremely high air temperatures and low relative humidity in summer [70].

On other hand, the Physiological Effective Temperature (PET) index that gives an estimation of the thermal sensation for indoors or outdoors can be calculated with the Ray man model, which is free access [74,76,77]. The model takes simple inputs and avoids all complications of the two-node model required by the Standard Effective Temperature (SET). The SET is the appropriate index for finding the relationship between thermal discomfort and physiological effect of wide range of environmental situations, clothing and activity levels including outdoor extreme weather conditions. The Universal Thermal Climatic Index (UTCI) also designed for wide ranges of activity, clothing, resistance and climatic conditions, can be calculated simply by using the UCTI free access calculator [78]. As it can be seen from the reviewed literature, there is no perfect or the best option in the index choice. Every index has its advantages and disadvantages inside its procedure so the users' choice might depend on the main and final objective of the assessment. Also, it is quite important the revision of the international standards developed by the International Standardization Organization (ISO) committee, i.e. ISO 7730 [79], about the thermal comfort in working environments, ISO 7243 [80], about the methodology for the estimation of the heat stress on a worker and ISO 7933 [71] related to the determination and interpretation of heat stress.

It can also be added that, during the literature search, any evidence about the application of any of those indexes on a thermal assessment specifically in CRS field was not found.

4. Non-ionizing radiation

The situation of being exposed to solar radiation at CRS in a daily basis is more often related to health impacts. The concerns about it, lead some international institutions to develop guidelines and assessment methodologies, establishing maximum permissible levels of exposure, in order to enable the employees to execute the risky tasks under the safest possible conditions.

One of these associations is The American Conference of Governmental Hygienists (ACGIH) [81], which published the exposure maximum limits called "Threshold Limit Values" (TLVs). The TLVs aim to allow the accomplishment of work without occurrence of negative health effects. These limits are based on data obtained from eye injury studies, as a result of looking directly to the sun and of being exposed to environments with strong visible radiant energy, e.g. deserts.

Sliney [62] in 1994, published a report about ocular hazards of light, which provides elements about human exposure limits based on the ACGIH´s threshold values for optical radiation (i.e., ultraviolet (UV), light and infrared (IR) radiant energy). In his work, Sliney argued that the TLVs usually work under the assumption of the visible radiant energy exposures that outdoors are not usually hazardous to the eye.

On the other hand, ICNIRP, in its way to the recognition of UV radiation as an occupational hazard cause, presented guidelines about limits of exposure and protection to UV, far infrared and non-ionizing radiation in general. In 2007 the commission published a standard with general information about UV exposures for both indoor and outdoor environments. Even though some preventive measures and maximum limits of UV exposure were suggested, it has been argued that the boundaries between the risks and the benefits of UV radiation are not quite clear. This fact means that, even if the UV health risks associated with excessive exposure are known, it is not clear if there are benefits from UV exposure above the levels in the guidelines [35–37]. Also, in its point 8.9, about outdoor exposure, it is clearly explained that the use of the guidelines in an outdoor setting poses many problems in the establishment of the dose. According to Sliney [36], the levels of exposure in mid-summer appear to exceed the limits, which happens in the opposite way for ocular exposure because it does not exceed the limits in long periods of time exposure under most situations. Even if the role of all factors is not yet clearly understood, the ICNIRP and the World Health Organization (WHO) strongly recommend the reduction of UV radiation exposures [37].

The standard about long far-infrared wavelengths exposures (IR-C radiation) focuses on the protection of high intensity artificial sources for industry workers in hot environments [82]; but the health hazards associated with hot environments, like heat strain and discomfort, are normally related with limits below thermal–injury due to IR-C exposures.

Among the European Standards,[2] provided by the European Committee for Standardization (CEN), are the EN-ISO-8996 [83] for the determination of the metabolic rate of workers and the EN-14255–3 [57] and EN-14255–4 [58] about the terminology and quantities used in UV, VL and IR exposure measurements.

The EN-14255-3 [57], in its own judgment, qualified the assessment methods suggested, per se, with lower accuracy and with limited precision. Also, it has been said that, due to the exception of some important factors such as posture, clothing and time spent outdoors, the standard has not direct relation to individual solar UV exposures, even though the safe limits are based on the MED instead of the SED. Since there are no limit values recommended based on the incidence of non-melanoma skin cancer due to radiant exposure, it has been proposed for skin cancer protection (in agreement with WHO and ICNIRP), the same sun protection used against erythema.

The widely concern leads the countries over the world to implement their own standards. E.g., the Spanish National institute of safety and health at work (abbreviation in Spanish; INSHT), in 2007, defined the methodology steps for the assessment of occupational exposures to optical radiation (UV, LV and IR) [34]. In a similar way, Venezuela published the standard COVENIN 2238:2000 [84] about non-ionizing radiation (180 and 315 nm) permissible limits, protection and control measures for occupationally exposed people and individual public members.

Meanwhile, the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA), in 2006, published a standard related to occupational UV exposure [85]; and in its Annex 3 provides information about avoiding occupational skin hazards. Also, there are two Mexican standards on this issue, developed by the government, one of them (NOM-013-STPS-1993) [86] about the safety and hygiene in workplaces with non-ionizing electromagnetic radiation, while the other (NOM-015-STPS-2001) [87] provides the WBGT method for the evaluation of thermal outdoor conditions.

5. Discussion

The number and the increments in production capacity of solar industry and the respective impact in jobs growth raised concerns of new health risks, over short timescales that need to be faced [43]. In global economy all people are valued and it is essential to provide working conditions that do not damage workers' health by following the principle of health for all human diversity. There has been a lot of research in how people respond to some environmental conditions and some of this gained knowledge has been included in international standards serving as the basis in working environment's design process, but the concept of identifying the requirements and design for all users has its owns limitations [88].

For example, ICNIRP guidelines have its limitation with the adequacy of the dose for the assessment in the eyes and skin. It resides in the fact that the ocular exposure limit of 30 J/m^2 is exceeded only when a person is looking directly to the sun, in summer and with clear sky conditions. It means that, under most conditions and in extreme exposure periods, the limit is not ever going to be exceeded, which appears quite remarkable for skin sensitive individuals who easily get sunburns [36,37].

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[2] European standards are applied in Austria, Belgium, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Norway, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, Switzerland and United Kingdom.

Otherwise some standards are basing the safe skin limits on the MED ending in a subjective measure determined by the reddening of the skin [57] which means that it is referred to the perceptible impact in the skin 24 h after being irradiated by the sun [35,37]. The MED should be applied individually to people with different types of skins [55]. If the main goal is the avoidance of sunburns, a general application to a population without considering the skin differences will be classified as a lack of prevention. On the other hand, applying it to all the individuals of a population is a time consuming task.

Djongyang et al. [89] claim that the actual standards about thermal comfort help, but should not be considered as absolute references. The ISO 7730, for example, has been criticized because of its lacks of theoretical validity [90]. The main problem for assessing the thermal outdoor conditions is that the variables might be more diverse than those for the indoor settings [91]. In reality, the conditions at work places are not uniform because the tasks are performed under a variation and combination of those conditions (degrees of physical work load, heat stress and work periods, types of clothing, gender, acclimatization, age, etc.) [65]. Besides these complex variables interactions, thermal comfort is defined so many times by the authors as that condition of mind which expresses satisfaction with the thermal environment; so, according to this definition, comfort is a subjective sensation [40,65–67]. Höppe [92], interviewed 250 people on a hot summer day, usually classified as thermally uncomfortable, but the curious fact was that most of the individuals perceived the weather conditions as comfortable conditions. One of the reasons showed that the interviewed population experienced a cold weather one day before the interview took place and the allowance of time to be spent outside made them happy. Finally, it was concluded that the tendency of people to perceive thermal conditions might be based on psychological aspects, which ends in subjective opinions, so such aspect must be included in the design of the methodology of the assessment.

The PET index is an example of the situation where subjective opinions are involved. For example, in a situation with a PET of 20 °C, a person on swimming trunks could feel very cold while wearing a coat would feel thermally uncomfortable. It happens because the protective clothing will promote sweating and will reduce the ability to evaporate and cool down [23]. Another example: a person with working load can evaluate the same conditions as “too warm” as well, while such thermal conditions at rest state would be regarded as “too cool”. Therefore, the method has to be adjusted to the subjective characteristics in terms of clothing and activity too [70].

The difficulties with various indices are that they provide different temperature thresholds with the same meaning of thermal sensations and/ or alert descriptions [75]. The interactions between the ambient temperature, radiant temperature, humidity, air velocity, clothing and metabolic rate are fundamental in defining the sensation of thermal comfort; at the same time to construct safety regulations become rather complex. The election of one index for the assessment depends on the final application purpose or the final user. It must be taken into account that almost all the indices that are based in real measures (direct indices) assumed a lack of the integration of variables comparatively with the indices based on the heat balance equation. Also, differs in difficulty [65], so if the objective is implementing the method in industry, which is the best option suited to practical use by personnel unskilled in psychometry? [93].

According to Parsons [23], the elements or principles about how people respond to thermal conditions, and how those conditions impact in human health, are well understood due to the extensively timeline studies. In other hand, the avoidance of unacceptable heat stress in specific populations and specific context through the application of those elements into guidelines is not yet well understood.

At the end, each occupational exposure situation must be evaluated individually for risks and benefits [2], because each environment has its own safety necessities of design and specificity. The central receiver solar power systems aren’t an exception. The need of a designed working environment for CRS, based on occupational safety and standards, where its particular necessities are included, seems a huge and challenging area of improvement opportunity.

6. Conclusions

Solar thermal plants are increasing in number and power generation capacity all around the world because of the motivation of countries to use renewable energy systems for electricity production. According to the literature, Central Receiver System (CRS) is the type of technology, among the CSP, moving to the forefront. It has Nowadays, it has been found that there exist evidence about risk assessments, carried on this kind of installations, and that they are linked to green jobs, where exposures to solar radiation lead to consequent health effects.

The CRS installations are environments with their own environmental conditions and their own safety necessities; therefore the design for the assessment has to be according to those needs. As it can be seen, from the reviewed literature, there is no perfect option as regards the chosen method of evaluation. Although every method inside its procedure has its advantages and disadvantages, the choice may depends of the main objective of the application. It might be recommended departing from de Appendix A, which is the first step in the hazard assessment and risk management process, for the identification of possible risk situations due to intense and/or prolonged exposure to solar radiation in CRS facilities. On the other hand, the use of Appendix C could be very helpful for the risks analysis methodology. The method of evaluation proposed here to be included in the methodology for the risk assessment should be based on the available time for the analysis, founds, equipment for data collection, psychological aspects involved, environmental aspects involved. Afterward, the risk estimation could be based on real data and/ or simulations of solar and thermal radiation; e.g., simulation of outdoor extreme environmental working conditions, or/and an assessment of thermal discomfort and optics through the measurement of direct and global radiation. In the following process, the analytical decisions to rank the order have to be applied based on most-to-least level of importance. Once the risk priority is settled and in order to have a working environment based on the idea of prevention, general measures for this type of installation (CRS) have to be defined. To accomplish such goal, it will be necessary to further study the human-interacting situations in CRS facilities, as listed in this paper. This will allow defining more clearly security and safety/good practices in working environments with the presence of solar radiation. Those security and safety recommendations, i.e. the specification of maximum permissible levels and dose, will improve the definition of location and the operation process of CRS solar facilities. In addition, there are other security elements applicable in working routines under safety conditions to be defined, such as protection for eyes and skin. The good practices of security and safety must be regulated by monitoring activities, starting the procedure by training the workforce.

The present literature review may be seen as a base of information, and a contribution, about maximum permissible levels of exposure, solar radiation effects and methods for the assessment of environmental conditions. It represents also a possible contribution for standards related with security principles in solar thermal energy industries.

Based on a framework of the occupational health needs in CRS working environments, the following tasks deserve to be considered, as well in future works: Assessment of the work conditions in solar energy installations; evaluation of glint and glare of reflected solar light from the receiver and heliostats surface; simulation of outdoor extreme environmental working conditions, definition of maximum safety levels and admissible doses of exposure to solar radiation; establishment of security and safety good practices related to working conditions; selection of criteria for the location and the operation on this kind of facilities; specification of safety measures such as maintenance routines, clothing sets and protective devices; proposition of a guideline.

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Appendix A

List of symbols

$\mathrm{F_{se}}$=Skin exposure Factor
$\mathrm{F_{se}}^*$=Corrected Skin exposure factor
$\mathrm{I_{UV}}$=UV index
$\mathrm{F_2}$=Cloud cover
$\mathrm{F_3}$=Duration of the exposure
$\mathrm{F_4}$=Ground reflectance
$\mathrm{F_5}$=Clothing factor
$\mathrm{F_6}$=Shade factor
$\mathrm{SCC_{risk}}$=Risk of squamous cell cancer
UV_{occ}=The exposures during the work
UV_{lunch}=The exposures during the lunch activity
UV_{recr}=The exposures during the recreational time
UV_{tot}=Cumulative UV dose
E_r=Retinal irradiance (W/cm^2)
d_r=Diameter of the image projected onto the retina ($f\,\omega$)
ω=Subtended angle from the source (rad)
d_s=Source size
r=Distance between the eye and the source
f=Focal length of the eye (m)
E_c=The irradiance in front of the cornea (W/cm^2)
d_p=Daylight adjusted pupil diameter (mm)
τ=Transmission coefficient
$E_{r,burn}$=Retinal burn threshold (W/cm^2)
$E_{r,flash}$=Potential after-image threshold (W/cm^2)
E_{beam}=Beam irradiance (W/cm^2)
E_{DNI}=Direct normal irradiance at the earth´s surface (1000 W/m^2)
ρ=Reflection coefficient
A_{obs}=Area seen by the observer
A'=Area of the reflecting surface
E_{ref}=Reflected irradiance
$\mathrm{E_c}$=Irradiance outside the cornea E'=Irradiance of the reflecting surface
A_p=Projected area
A_{obs}=Observed area
r_{obs}=Observer distance
A_n=Area of the $\boldsymbol{n}$ heliostats
E_n=Irradiance of the $\boldsymbol{n}$ heliostats

List of abbreviations

NERL=National Renewable Laboratory
NIR=Non-Ionizing Radiation
UV=Ultraviolet radiation
UV-A=Ultraviolet radiation type A
UV-B=Ultraviolet radiation type B
UV-C=Ultraviolet radiation type C
VL=Visible light
IR=Infrared radiation
IR-A=Infrared radiation type A
IR-B=Infrared radiation type B
IR-C=Infrared radiation type C
CSP=Concentrated solar power
CRS=Central receiver system
OSHA=Occupational Safety and Health Administration
EU- OSHA=European Occupational Safety and Health Agency
BLS=Bureau of Labor Statistics
USA=United States of America
TSF=The Solar Foundation
IRENA=International Renewable International Agency
ICNIRP=International Commission on Non-Ionizing Radiation Protection
SED=Standard Erythema Dose
MED=Minimal Erythema Dose
MM=Melanoma
BCC=Basal Cell Cancer
SCC=Squamous Cell Cancer
WBGT=Wet- bulb globe temperature
PMV=Predicted Mean Vote
PET=Physiological Effective Temperature
SET=Standard Effective Temperature
UTCI=Universal Thermal Climatic Index
ACGIH=American Conference of Governmental Hygienists
TLVs=Threshold Limit Values
WHO=World Health Organization
ISO=International Standardization Organization
CEN=European Committee for Standardization
INSHT=National institute of safety and health at work
ARPANSA=Australian Radiation Protection and Nuclear Safety Agency

Appendix B

See Table B.1.

Table B.1
Solar radiation effects in health[a].

Wavelength (nm)	Affected area	Primary effects	Description	Secondary effects	Side effects
Irreversible physiological effects					
380–1400 nm UVA-VL-IR	Ocular	Thermal eye lesions	Most of the useful vision is lost	Burns in the retinal tissue	
1400–3000 nm-10 μm IRB, IRC	Ocular		Protein coagulation of the front and middle layers, and ulcers	Burns in the cornea	
315–400 nm UVA; 780–3000 nm IR	Ocular		Opacities in the lens	Cataracts	
180–400 nm UV	Ocular		Inflammation on the cornea (the feeling of sand in the eye)	Keratitis	
400–700 nm VL; 780–3000 nm IR	Ocular		Vision loss in a portion of the visual field	Scotoma	
380–700 nm UV-VL	Ocular		Inflammation of the retina of the eye	Retinitis	
–	Nervous system	Heat stroke	The regulation temperature system of the body fails when the body temperature rises, the sweating mechanism fails and the body is unable to cool down itself	Confusion, consciousness loss, convulsions, lack of sweating, dry skin, very high body temperature and hallucinations	Death
315–1400 nm UVA-VL-IR	Skin	Photoaging	The skin is marked by fine lines and a modest skin laxity.		
290–400 nm UV	Skin	Photo-immunosuppression	The immune skin system is not available to recognize and destroy the invading pathogens and/ or skin cancer cells	Skin cancer	
Reversible physiological effects					
400–780 nm VL	Ocular	Glare disability	Veiling luminance (scattered light) in the human eye which reduces the contrast in the scene	Reduction of the visual performance, flash blindness, after image and retinal burns	Falls or other kind of accidents ended in injuries
400–780 nm VL	Ocular	Glare discomfort	Continues exposure to a bright source that reduces the ability to see details in the area of the visual field	Headaches	Falls or other kind of accidents ended in injuries
400–780 nm VL	Ocular	Afterimage	Blind spot in the visual field which persists from seconds to a few minutes after the light in no longer in the visual perimeter		Falls or other kind of accidents ended in injuries
400–780 nm VL	Ocular	Flash blindness	Immediate and temporary vision loss produced when the retinal light-sensitive pigments are bleached by the intensity of light (usually the eye is exposed to higher intensities of those that it is adapted at that moment)		Falls or other kind of accidents ended in injuries
400–780 nm VL	Ocular	Luminance flicker	Temporal intensity modulations of bright lights	Vertigo, disorientation, mild headaches, muscle spasm ended in convulsions and epileptic seizures	Falls or other kind of accidents ended in injuries
290–700 nm UV-VL	Skin	Photo-sensitivity (Photodermatoses)	continues exposures that produce a sensitization phase resulting in a delayed-type of hypersensitivity reaction	Photoallergy and/ or Phototoxicity	Solar urticaria, porphyrias, polymorphus, light eruption, hiroa vaciniforme, actinic, prurigo, chronic actinic, dermatitis and others
380–3000 nm UVA-VL-IR	skin	Sunburns	Skin tissue injury caused by the exposure to sun radiation	Red appearance of the skin due to the increment in blood content near the sink surface	Erythema (180–400 nm): skin redness, edema, pain and skin swelling Apoptosis: delayed cell killing
–	Skin	Heat rash	Pricking sensations during heat exposure	Skin irritation due to the excessive seating during hot and humid weather conditions	
–	Skin	Anhidrotic heat exhaustion	Extensive areas of skin with no sweating but with gooseflesh appearance	Skin trauma (heat rash, sunburn) causes sweat retention in skin and reduce evaporative cooling	Temporary heat intolerance
–	Nervous system	Heat exhaustion	Dehydration (loss of water and salt) and depletion of circulation blood volume	Fatigue, nausea, headache and giddiness, skin clammy and moist, pale complexion, muddy or hectic flush, may faint on standing with rapid thready pulse and breathing, and low blood pressure	

–	Nervous system	Heat syncope	Lack of acclimatization by a prolonged standing or sudden rising from a sitting or lying position and dehydration	Light- headedness, dizziness and fainting	
–	Nervous system	Heat cramps	Loss of body salt in sweat, water intake dilutes electrolytes, water enters to muscles causing spasm	Painful spasms of muscles used during work activities such as arms, legs and/ or abdominal	Heat exhaustion
Psychological effects					
/	Nervous system	Transient heat fatigue	Behavioral disorders	Discomfort and physiologic strain	Decrement in productivity
/	Nervous system	Chronic heat fatigue	Behavioral disorders	Psychosocial stress produce by the hormonal imbalance	Decrement in productivity

The effects differs in severity or has a low capability of impact in human health depending of the intensity of the source and time of exposure. Some of impacts begin as reversible effects and end as irreversible effects due to continue exposures in time.

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Appendix C

This appendix address some examples about the evaluating methods explained on Section 3 with the objective of illustrating more clearly the application of the formulas from that section.

Looking directly to the sun

As an example, presented in Ho et al. [15], the retinal irradiance caused by viewing the sun directly can be calculated by using the following formulas.

$$E_r = E_c\left(\frac{dp^2}{dr^2}\right)\tau \tag{C.1.}$$

$$\omega = \frac{d_s}{r};\ d_r = f\omega \tag{C.2.}$$

where the parameters are set as: $E_c = 0.1\ \mathrm{W/cm^2}$, $d_p = 0.002$ m, f=0.017 m, $\omega = 0.0094$ rad and $\tau = 0.5$.

As a result a typical value for the retinal irradiance is around $E_r = 8\ \mathrm{W/cm^2}$.

Direct specular reflections from the surface of the heliostats assessment

Subtended angle of the reflected image on a mirror as observed from a given distance

$$\omega_{spot} = \beta\sqrt{\frac{E_{beam}}{\rho E_{DNI}}};\ E_{beam} = E_c \tag{C.3.}$$

Retinal Irradiance (from specular reflections)

$$E_r = \frac{\rho E_{DNI} {d_p}^2 \tau}{f^2\beta^2} \tag{C.4.}$$

Suggested information

1. Eq. (C.2.) can be used to determine the equivalent retinal irradiance for comparisons against the safe retinal irradiance metrics.
2. The Eq. (C.2.) to convert the E_c to E_r is used where the angle, ω, is taken from the subtended angle, ω_{spot} (subtended angle of the reflected image on a mirror as observed from a given distance in Eq. C.3)
   - Where the parameter can be set at: $\beta = 9.4$ mrad, $\rho = 0.92$, $E_{DNI} = 0.1\ \mathrm{W/cm^2}$, $d_p = 0.002$ m, f=0.017 m, and $\tau = 0.5$.

Comparing with the maximum limits for exposures to the eye:

$$E_{r,burn} = \frac{0.118}{\omega}\ for\ \omega < 0.118\ rad \tag{C.5}$$

$$E_{r,burn}{=}1\ for\ \omega{\geq}0.118\ rad\ E_{r,flash} = \frac{3.\,59\times10^{-5}}{\omega^{1.77}} \tag{C.6}$$

Skin

Corrected skin exposure factor by Wolska [46]

For a construction worker

$$\mathbf{F_{es}} = \mathrm{I_{UV}}{*}\mathrm{F_2}{*}\mathrm{F_4}; \tag{C.7}$$

$$\mathbf{F_{es} = 7.3{*}1{*}1 = 7.3}$$

$F_{es} \le 1$ Low risk, no additional preventive measures needed.
$F_{es} > 1$ preventive measures are necessary

Then, the correction of the F_{es} factor:

$$\mathbf{F_{es}}^* = \left(F_{es}\right)^*\left(F_3\right)^*\left(F_5\right)^*\left(F_6\right) \le 10SED \tag{C.7′}$$

$\mathbf{F_{es}}^* = 7.3^*0.5^*1^*3.65 = 13.35$, which corresponds to high risk.

Skin cancer estimation by Milon et al. [38]

The cumulative UV dose was estimated for a person in the age of T = 60 years with an outwork history of 25 years, but a person who took his or her lunch indoors. So the cumulative dose was expressed as the sum of the exposures during the work and lunch along "y" years of an occupational activity and recreational time from 0–T.

$$\sum_0^{60} UV_{tot} = \sum_{y=T}^{T+25} \left(UV_{occ} + UV_{lunch}\right) + \sum_0^{60} UV_{recr} \tag{C.8}$$

The UV_{occ}, and UV_{lunch} were obtained from SimUVEx model, and UV_{recr}, from a survey.

The facial exposure of full -time outdoor worker with the lunch excluded was 1604 SED (an average of 5.8 SED per workday). The MED for skins types II and III in Fitzpatrick skin pigmentation scale is between 2.5 and 3 SED respectively.

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