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Design Factors in Concentrating Solar Power Plants for Industrial Steam Generation

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Abstract. The importance of energy consumption for industrial steam generation justifies the need to promote new renewable and environmentally friendly energy sources, such as concentrated solar energy, for its integration in this sector. In this work, the different alternatives currently available and their advantages and disadvantages are discussed, as well as the main parameters that influence the design of solar installations for industrial steam production. Besides, a guidance procedure is proposed and applied to a real solar plant design.

Key words. Solar plant, process heat, steam generation, lineal Fresnel collector, kettle reboiler

1. Introduction

Industrial consumption currently accounts for a significant percentage of total primary energy demand, and in this case, the production of thermal energy (mainly for its use as process heat) represents a larger fraction compared to other sectors such as the residential one [1],[2]. The use of fossil fuels as an energy source to meet the growing demand has disadvantages related to greenhouse gas emission, dependence on foreign countries, or resource depletion, being nonrenewable resources. Prospects for the future show a consumption growth once the Covid-19 crisis effects end [3], and concentrating solar thermal energy maybe become a viable alternative in regions with good radiation levels throughout the year.

Multiple studies have been conducted in recent years on existing linear focus solar collector technologies (linear Fresnel collectors, LFC, and parabolic trough collectors, PTC), namely the design and optimization of the main components of these systems [4]-[7], the analysis and comparison of different technologies and configurations [8]-[10], and other works about optical and thermal losses and efficiency [11]-[13].

However, there are fewer studies focused on the integration of this type of plants in industrial processes, and they mainly target the viability of their use in different sectors and applications, or they focus on specific cases like low-temperature systems and flat plate collectors [14],[15], PTC or hot water production [16],[17].

F. J. Sepúlveda et al conducted a series of energy audits in several industries to analyze the potential for LFC implementation and the influence of different factors like the thermal energy ratio, the fraction of the working schedule that coincides with sunlight time, or the production seasonality [18].

The study of the most relevant factors that determine the design process of a solar power plant for steam generation is, therefore, interesting to promote this type of promising technologies. In this work, these parameters are evaluated, and tools to facilitate decision-making are proposed and subsequently applied to the real case of a concentrating medium temperature prototype in an industry located in southwestern Spain.

2. Materials and methods

The main parameters that affect the design process of an industrial steam generation concentrating solar plant are both technological factors (such as the solar technology used, the steam generation system, or the heat transfer fluid (HTF) type), and factors related to the chosen location, as shown in Figure 1. The component sizing process and the final behavior of the plant will depend on these factors.

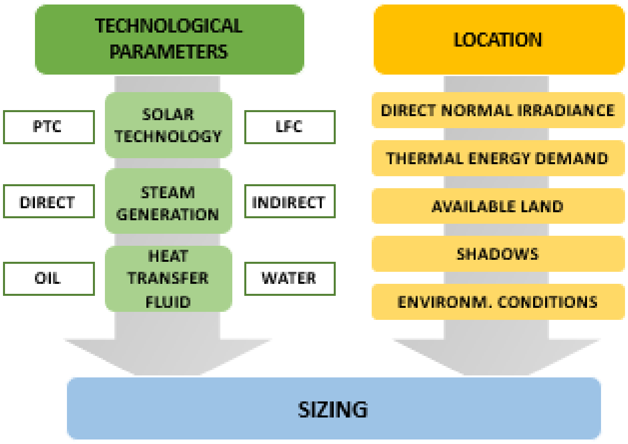

Fig. 1. Main design parameters

A. Technological parameters

1) Solar technology.

In order to seize the thermal energy provided by solar radiation, different systems must be used to transmit this energy to a heat transfer fluid that facilitates its transport and exploitation.

Technologies such as flat plate collectors cannot achieve the necessary conditions to produce steam for industrial uses [19], so more complex systems must be chosen, like solar tracking mirrors which concentrate the energy received as direct radiation for better performance.

Point focus solar concentrating technologies, like central receiver power plants and parabolic dish Stirling engine systems, use complex two-axis tracking technologies and high concentration ratios to reach high- temperature levels [20]. Thus, the selection process will approach linear focus systems: LFC and PTC, which are technologies with single-axis tracking suitable for medium temperature applications, that also strike a balance between cost and complexity of the system and the energy production obtained.

The main advantages that LFC have over PTC, such as their greater structural simplicity, the use of flat mirrors with less weight and size, a lower energy consumption when tracking the sun path, the smaller surface area required, and, in short, up to a 55% lower cost [21], can compensate the lower optical performance of these components [22] and make them appropriate for industrial facilities.

Other favorable characteristics of LFC are the possibility of using independent tracking and control systems for each mirror row, which implies that, if one of them fails, the impact on production levels will be less important; the sealing of hydraulic connections will be easier since the absorber tube does not rotate, and there will be fewer shadow problems.

In conclusion, it is a very promising technology in the field of industrial steam production, it is adapted to the requirements of this sector and its use can be favorable from a technical and economic point of view [18].

2) Steam generation system

Regarding steam productions, two different systems can be chosen: the direct system, in which there is a single circuit that includes the absorber tube, where the water receives the energy input from the mirror field and vaporizes, and the indirect system, which has a second circuit where the steam generation process takes place.

In the direct system, it will be necessary to preheat the HTF so that it reaches the absorber tube in conditions suitable for the subsequent steam generation, and a steam separator must be included to prevent that water drops reach the steam distribution circuit in liquid state.

Moreover, the selection of an indirect system requires the installation of a heat exchanger that links the primary and secondary circuits, so that inside it the HTF transmits the absorbed energy to the water to be vaporized. The choice of a kettle reboiler type exchanger, in which the primary fluid circulates through the tubes and the secondary fluid stays in the shell, would avoid having to install a steam separator, as it provides dry saturated steam.

The heat source used in a solar power plant is discontinuous, which makes it difficult to control the phase change process. One advantage of the indirect generation system is that it prevents steam formation inside the absorber tube, so there is no phase change in the primary circuit and there is more inertia as the generated steam accumulates inside the exchanger, which also maintains pressure and temperature conditions and stabilizes production. In the direct system, however, there will be a two-phase flow that generates control and stability problems [1].

In addition, the indirect system introduces the possibility of employing a different HTF apart from the water used to generate steam, with characteristics that improve its behavior (thermal oils, or water with additives that prevent freezing). The main objection is that there must be a temperature difference between the two fluids to guarantee an efficient heat exchange between both circuits, so the primary must be properly pressurized to avoid vaporization at high temperatures, and thermal oils or other fluids which can work under these conditions must be used.

It is common to work with direct steam systems, but there are some industrial applications in which steam pressure needs are low [18], and in these cases, indirect heating installations that facilitate the control of the steam generation process may be of interest. Thus, the disadvantage of vapor formation inside the tubes is eliminated, and when working with moderate pressures and temperatures, water can be used as HTF, which avoids the environmental or safety drawbacks that characterize thermal oils.

3) Heat transfer fluid

Several types of fluids can be employed to transport the energy which has been concentrated in the solar field. The use of air and other gases, although it has certain advantages, is currently not widespread. Fluids like molten salts or liquid metals are suitable for temperature levels higher than those required for industrial steam generation, and they have disadvantages such as the risk of solidification at low temperatures, their dangerousness, their cost, or their difficult handling [23].

The two most viable options for small-scale industrial applications are water and thermal oils. The use of oils has some drawbacks as they are extremely flammable, toxic, and polluting fluids, so a spill would cause a serious environmental impact and other security issues. In addition, they increase the complexity of the installation. However, for applications in which, due to the characteristics of steam consumption in the industry where the plant is located, high pressures must be reached, the use of oil may be the only valid alternative.

Water is, therefore, the first option to be weighed, since it has a good heat capacity, its use is safe, and it simplifies the system and decreases its cost [23]. The applied treatments must try to avoid excessive corrosion of the components, their degradation, and the accumulation of dirt. The main existing LFC electric power plants currently use water as HTF [9].

B. *Location*

The placement of the installation is the last of the factors influencing its design, and it must meet a series of requirements to guarantee that a significant part of the thermal energy demand is covered by the solar resource and to ensure proper operation of the plant, such as the existence of adequate levels of solar radiation (direct normal irradiance, DNI) or a sufficient area to locate the solar field (which will be the largest system in the plant). Shadows cast by existing obstacles and other environmental conditions must also be considered.

1) Direct normal irradiance (DNI)

The first variable that must be verified to assess the viability of the plant in a specific industry is the availability and quality of the resource which will be used, solar radiation. Most of the Spanish peninsular land, and especially the southern regions, is characterized by a Mediterranean-type climate with little rainfall and many hours of sunshine [24]. However, besides the general characteristics of the region where the facility will be located, possible microclimates that may influence radiation levels should be studied, so it is important to have accurate meteorological data from an area close to the plant environment [25].

It is also important to take into account other local factors such as the orography of the land, or shadows that the surrounding buildings may cast over the space proposed for the plant, which must have the necessary connections for supplies like electricity or water.

2) Thermal energy demand

Another relevant parameter is the company's thermal energy demand, although it should only be considered for guidance since in most cases it will not be possible to size the plant to fully cover the steam needs of the industry, as other factors (economical ones, or land availability) will be the most limiting. In any case, as it is a variable and most times unpredictable source of energy, an alternative must be available for the correct operation of the industry when the solar resource is not available.

Apart from the percentage of demand covered by the solar system, the profitability of the installation will be influenced by other factors, for example, the fuel that is intended to be replaced by the plant, its price, the seasonality of consumption [18], or possible subsidies from public administrations.

3) Available land

Available land in the industries facilities is one of the most limiting resources for the implementation of concentrating solar technologies, and it can be among the design parameters that determine the viability and cost-effectiveness of the plant. According to N. El Gharbi et al, LFC need a surface of 4-6 m^2 for each MWh generated per year, while 6-8 m^2 per MWh will be necessary in the case of PTC technologies [22].

Depending on the selected collector model, its dimensions and proportions will influence the final number of modules that can be installed. Apart from the available space and the area needed by each collector, aspects such as the relationship between the dimensions of the place and the size of each module must be taken into account to determine how many of them can be connected in series, which will condition the temperature gradient and the primary fluid flow rate.

Once the radiation levels and the mirror area are known, it is possible to estimate the power output of the plant and the energy generated under standard conditions. These results, which will also be influenced by shading and environmental conditions at the location, will make it possible to verify what fraction of the company's thermal energy demand can be covered.

For this purpose, the optical model developed by F.J. Sepúlveda et al [26] was used to obtain the total efficiency, η_t, which relates the net heat absorbed by the fluid inside the tube (using the flow rate, $\dot{m}$, and the temperature difference, T_o-T_i) to the theoretical radiation at each instant according to (1), simulating the losses throughout the year.

$$\eta_t = \frac{\dot{m} \cdot C_p \cdot (T_o - T_i)}{Rad_{theor}} \quad (1)$$

Finally, the previously calculated total efficiency, η_t, the DNI (in W/m^2), and the total mirror surface, S_t, in m^2, were used to obtain the plant's solar power applying equation (2).

$$P_s = \eta_t \cdot DNI \cdot S_t \quad (2)$$

Additionally, the selected space may also condition the orientation of the solar field, defined as the angle formed by the axis of the absorber tube and the south direction, and as a consequence, the energy production of the plant, the annual generation being higher in a North-south orientation, with higher peaks in summer and lower production in winter, while an east-west orientation provides somewhat lower total levels, but more balanced between the different months.

4) Shadows

It is necessary to carry out a specific analysis of shadows in the chosen placement, such as those caused by existing buildings, since they affect the availability of solar radiation and, therefore, the viability of the plant itself.

First, to represent the building's shadow profile graphically, the main points that define its profile must be identified using horizontal and vertical distances from the selected location, and the main angles corresponding to those points (namely azimuth and elevation) must be calculated.

Secondly, the sun path diagram must be elaborated to determine the position of the Sun in the sky throughout the year. The equations that determine the movement of the Earth in relation to the Sun were obtained from [27].

It is necessary to know the arc of circumference described by the Earth around the Sun, B, given by (3), where n is the day of the year. Thus $1 \leq n \leq 365$.

$$B = (n-1)\frac{360}{365} \tag{3}$$

Solar time, ST, can be obtained using the standard time, T, and the difference in longitude between the observer's meridian, L_{loc}, and the meridian used to define the local standard time, L_{st}, according to (4):

$$ST = T + 4(L_{st} - L_{loc}) + E \tag{4}$$

The parameter E can be found using the equation of time (in minutes) expressed by (5):

$$E = 229.2(0.0000075 + 0.001868\cos B - 0.032077\sin B - 0.014615\cos 2B - 0.04089\sin 2B) \tag{5}$$

Solar altitude angle, α_s, and solar azimuth angle, Az, are given by (6) and (7):

$$\alpha_s = sin^{-1}(\cos\phi\cos\delta\cos\omega + \sin\phi\sin\delta) \tag{6}$$

$$Az = cos^{-1}\left(\frac{\sin\alpha_s\sin\phi - \sin\delta}{\cos\alpha_s\cos\phi}\right) \tag{7}$$

Where ϕ is the latitude of the place and δ is the declination angle, which can be found from Spencer (1971) equation as follows (8):

$$\begin{aligned}\delta = 0.006918 - 0.399912\cos B + 0.070257\sin B \\ -0.006758\cos 2B + 0.000907\sin 2B \\ -0.002679\cos 3B + 0.00148\sin 3B\end{aligned} \tag{8}$$

Finally, hour angle, ω, which is the angular displacement of the sun east or west of the local meridian due to rotation of Earth, is determined by (9):

$$\omega = (12 - ST)\cdot 15 \tag{9}$$

5) Environmental conditions

There are also other factors related to the location of the plant that affect its operation, such as wind and other adverse meteorological phenomena, which can cause damage to the equipment, or dust and other contaminants, which can be deposited on the surface of the mirrors or the absorber tube, affecting the performance of the installation by decreasing the reflectivity of the components [28].

Necessary measures should therefore be taken to ensure proper operation of the plant, such as frequent and adequate cleaning of reflective elements or stopping the plant and placing the mirrors in a safe position when the wind exceeds potentially dangerous speeds.

3. Results

Once the parameters that influence the design of concentrating solar power plants for steam production and the different existing alternatives were known, the procedure proposed in this work was applied to the real case of a small experimental prototype, located in an industry in the province of Cáceres (Extremadura, Spain).

Despite its experimental nature, locating the prototype on land provided by an operating industry has given an insight into the limitations that a real installer will have to face when starting this process, such as surface and orientation restrictions imposed by the characteristics of the available space, which will be different from the theoretically more favorable options.

The solar concentration technology selected was a LFC system, in accordance with the advantages of its use compared to PTC, such as its greater simplicity and lower cost, which will make its installation attractive to interested companies. In addition, from the technical and scientific point of view with which the solar installation was proposed, as it is a less known but equally viable system, LFC technologies were more interesting due to their innovative characteristics.

An indirect steam generation system was finally chosen, as it was considered to facilitate the control of the heat transfer and phase change process, and due to the characteristics of the steam, since consumption in the industry's facilities requires low pressures of about 4 bar, which will be increased to a maximum of about 7 bar for testing. Therefore, the conditions are suitable for an indirect steam system, as the saturation temperature corresponding to the maximum 7 bar that will be reached in the secondary circuit will be 165 °C, so that excessive temperatures in the primary circuit will not be necessary to guarantee the thermal gradient for heat exchange.

Regarding the heat exchanger, a kettle reboiler was used, so the hot primary fluid flows through the tube bundle and transfers the energy absorbed in the solar field to the liquid water on the shell side, providing dry saturated steam at the outlet without having to include an additional separator afterwards.

The last of the technological parameters was the HTF, and in this case it was decided to use treated water from the industry's supply system, as it is a safe, cheap, and non-polluting fluid that adequately withstands the pressures expected during the normal operation of the solar installation.

After studying the technological parameters, we proceeded to analyze the different factors related to the location of the plant, which also determine its viability and design.

The prototype was installed in a space provided by a factory in the province of Cáceres, in southwestern Spain, which has very favorable conditions for the implementation of solar plants. Although direct radiation levels over the whole year are higher in other more arid regions in the southeast of Spain, yields are expected to be high in the summer months as can be seen in Figure 2, since Cáceres is the city that receives the most direct radiation in July, specifically 6,37 kWh/(m^2·day) [24].

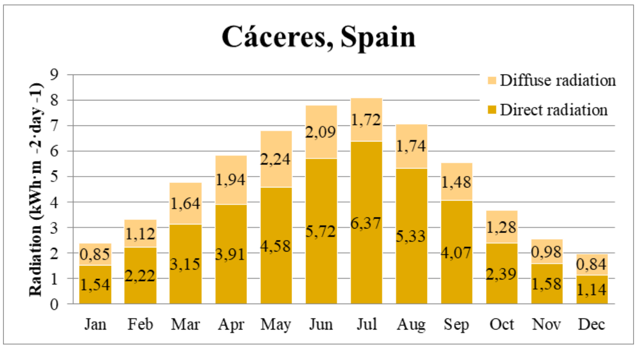

Fig. 2. Monthly radiation levels at the plant location.

The company suggested a traffic roundabout placed to the south part of the factory site, with dimensions of 31.5 m by 16.5 m, as shown in Figure 3. The selected collector model has a total of 10 rows of mirrors with a net aperture of 26.4 m^2, requiring a space of about 6 m by 6 m for their placement, according to the data provided by the manufacturer. To make the best use of the available space, it was decided to orient the solar field in the direction of the longest axis of the selected area, that is, an orientation of about 135º. Therefore, considering the dimensions, the separation between modules, or the space for the placement of auxiliary equipment, a total number of 4 collectors were installed. Using this value, along with the analysis of direct radiation, losses, and efficiency, a nominal power of the solar field equal to 56.4 kW was obtained.

Fig. 3. Solar plant location

As mentioned, the shape of the chosen place led to the choice of a 135º orientation, so intermediate results between the north-south and east-west options are expected. This fact is interesting since it will allow us to know the efficiency and production provided by an orientation different from the optimal one.

Furthermore, by applying the proposed equations, the industry profile and the sun path corresponding to some significant days were determined as shown in Figure 4, and obstacles that cast shadows over the plant were found. In this case, shadows will appear only when the Sun is at a very low position and radiation is well below the minimum required for steam production, so the chosen placement is correct.

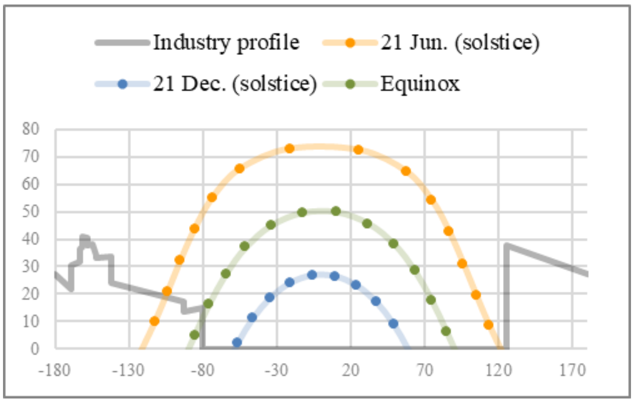

Fig. 4. Sun path and shadow profile of the industry.

Finally, regarding the environmental conditions, it is an industrial site with vehicle traffic and a rural environment, so some fouling of the mirrors is expected but will not interfere too much with their performance, although periodic cleaning with pressurized water is planned.

The actual appearance of the solar plant in its real location, including the Fresnel collectors, the absorber tube of the primary circuit, and the power block which includes the kettle reboiler and the secondary circuit, is shown in Figure 5.

Fig. 5. View of the solar plant

4. Conclusions

The main factors affecting the design of concentrating solar power plants for process steam generation have been set. They have been evaluated theoretically and applied to a real case.

Fresnel technology meets the needs of industry, is easy to control and cost-effective. It is advisable, if the consumption characteristics are adequate, to use an indirect steam system and water as heat transfer fluid, as it avoids many inconveniences.

In terms of sizing, the most limiting parameter is the available surface area, and conditions such as direct radiation and shading must be checked.

A design has been proposed for an experimental prototype, with solar power equal to 56.4 kW, whose performance will be studied through the planned operational tests.

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References

[1] M. Mokhtar et al, "Direct Steam Generation for Process Heat using Fresnel Collectors", International Journal of Thermal & Environmental Engineering (2015). Vol. 10, pp. 3-9.
[2] S.H. Farjana et al, "Solar process heat in industrial systems - A global review", Renewable and Sustainable Energy Reviews (2018). Vol. 82, pp. 2270–2286.
[3] International Energy Agency, World Energy Outlook 2020, OECD Publishing, Paris (2020).
[4] J. Zhu and H. Huang, "Design and thermal performances of Semi-Parabolic Linear Fresnel Reflector solar concentration collector", Energy Conversion and Management (2014). Vol. 77, pp. 733–737
[5] R. Abbas et al, "Design of an innovative LFC by means of optical performance optimization: A comparison with PTC for different latitudes", Solar Energy (2017). Vol. 153, pp. 459–470.
[6] P. Boito and R. Grena, "Optimization of the geometry of Fresnel linear collectors", Solar energy (2016). Vol. 135, pp. 479-486.
[7] E. Bellos, "Progress in the design and the applications of Linear Fresnel Reflectors - A critical review", Thermal Science and Engineering Progress (2019). Vol. 10, pp. 112-137.
[8] R. Abbas et al, "PTC or LFC? A comparison of optical features", Solar Energy (2016). Vol. 134, pp. 198-215.
[9] M.J. Montes et al, "A comparative analysis of configurations of LFC for concentrating solar power", Energy (2014). Vol. 73, pp. 192-203.
[10] N. Kincaid et al, "An optical performance comparison of three concentrating solar power collector designs", Applied Energy (2018). Vol. 231, pp. 1109-1121.
[11] S. S. Sahoo et al, "Analysis of heat losses from a trapezoidal cavity used for Linear Fresnel Reflector system", Solar Energy (2012). Vol. 86, pp. 1313-1322.
[12] M. Cagnoli et al, "Analysis of the performance of LFC: Encapsulated vs. evacuated tubes", Solar Energy (2018). Vol. 164, pp. 119-138.
[13] F. Huang et al, "Optical performance of an azimuth tracking linear Fresnel solar concentrator", Solar Energy (2014). Vol. 108, pp. 1-12.
[14] J.A. Quijera et al, "Integration of a solar thermal system in canned fish factory", Applied Thermal Engineering (2014). Vol. 70, pp. 1062-1072.
[15] T.G. Walmsley et al, "Integration options for solar thermal with low temperature industrial heat recovery loops", Energy (2015). Vol. 90, pp. 113-121.
[16] R. Silva et al, "Modeling and co-simulation of a parabolic trough solar plant for industrial process heat", Applied Energy (2013). Vol. 106, pp. 287-300.
[17] B. El Ghazzani et al, "Thermal plant based on PTC for industrial process heat generation in Morocco", Renewable Energy (2017). Vol. 113, pp. 1261-1275.
[18] F.J. Sepúlveda et al, "Analysis of Potential Use of LFC for Direct Steam Generation in Industries of the Southwest of Europe", Energies (2019). Vol. 12, 4049.
[19] A. Franco, "Methods for the Sustainable Design of Solar Energy Systems for Industrial Process Heat", Sustainability (2020). Vol. 12, 5127.
[20] Soteris A. Kalogirou, "Solar thermal collectors and applications", Progress in Energy and Combustion Science (2004). Vol. 30, pp. 231-295.
[21] G. Morin et al, "Comparison of LF and PTC power plants", Solar Energy (2012). Vol. 86, pp. 1–12.
[22] N. El Gharbi et al, "A comparative study between PTC and LF reflector technologies", Energy Procedia (2011). Vol. 6, pp. 565–572.
[23] K. Vignarooban et al, "Heat transfer fluids for concentrating solar power systems - A review", Applied Energy (2015). Vol. 146, pp. 383-396.
[24] J. M. Sancho Ávila et al, Atlas de Radiación Solar en España utilizando datos del SAF de Clima de EUMETSAT, Agencia Estatal de Meteorología (2012).
[25] M. Schlecht and R. Meyer, Concentrating Solar Power Technology: Principles, Developments and Applications, Woodhead Publishing (2012), pp. 91-119.
[26] F.J. Sepúlveda et al, "Development and design of a software tool for optical simulation of Fresnel collectors", V Congresso Ibero-Americano de Empreendedorismo, Energia, Ambiente e Tecnologia (2019).
[27] J.A. Duffie and W.A. Beckman, Solar Engineering of Thermal Processes, third ed., John Wiley & Sons, New York (2006).
[28] T. Sarver et al, "A comprehensive review of the impact of dust on the use of solar energy", Renewable and Sustainable Energy Reviews (2013). Vol. 22, pp. 698-733.