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Environmental impacts of large-scale CSP plants in Northwestern China

Zhiyong Wu[a,*], Anping Hou[b], Chun Chang[a], Xiang Huang[c], Duoqi Shi[b], Zhifeng Wang[a]

Several concentrated solar power demonstration plants are being constructed, and a few commercial plants are announced in northwestern China. However, the mutual impacts between the concentrated solar power plants and their surrounding environments have not yet been addressed comprehensively in literature by the parties involved in these projects. In China, these projects are especially important as an increasing amount of low carbon electricity needs to be generated in order to maintain the current economic growth while simultaneously lessening pollution. In this study, the authors assess the potential environmental impacts of large-scale concentrated solar power plants. Specificly, the water use intensity, soil erosion and soil temperature are quantitatively stressed. It was found that some of the impacts are favorable, while some impacts are negative relative to traditional power generation and some need further research before they can be reasonably appraised. In quantitative terms, concentrated solar power plants consumes about 4000 L/MWh of water if wet cooling technology is used, and the collectors lead to the soil temperature changes of between 0.5-4 ℃ while on the other hand it was found the soil erosion is dramatically alleviated. The results of this study are helpful to the decision maker in concentrated solar power site selection and regional planning. Some conclusions of this study are also valid for large-scale photovoltaic plants.

Key words: CSP plant, soil erosion, soil temperature, water use environmental impacts;

1. Introduction

Energy and ecological environment are the material foundations on which the human beings live. Since the reform and opening-up of China in the early 1980's, China's economic development has made remarkable achievements, and has also made significant contributions to the world's development and prosperity. However, China's environment has paid a heavy price for the economical achievements. The contradictions between energy demand and environment is increasingly prominent in China. The continuing deterioration of the environment has now become a serious impediment to China's further development, and will endanger the living and survival of the Chinese people in the future if nothing is done to change the situation [1, 2].

Solar energy is one of the earliest energy which human beings knew and harnessed, and has always been considered unlimited, and clean. Most northwest regions of China have abundant solar resource and thus can be considered as the future energy base of China, see Fig. 1 for the solar radiation distribution in China. In fact, solar powered electricity generation has been experiencing rapid growth in recent years. According to the 12th Five-Year Plan (2011-2015), China will build 1 GW of concentrated solar thermal power plants and 20 GW of photovoltaic power plants. However, the real developing pace of solar power plants far exceeds the plan. For example just in 2013 alone, China had installed an astounding new solar PV capacity of 13 GW. Furthermore the state council predicted the cumulative PV capacity should exceed 35 GW by the end of 2015 [3].

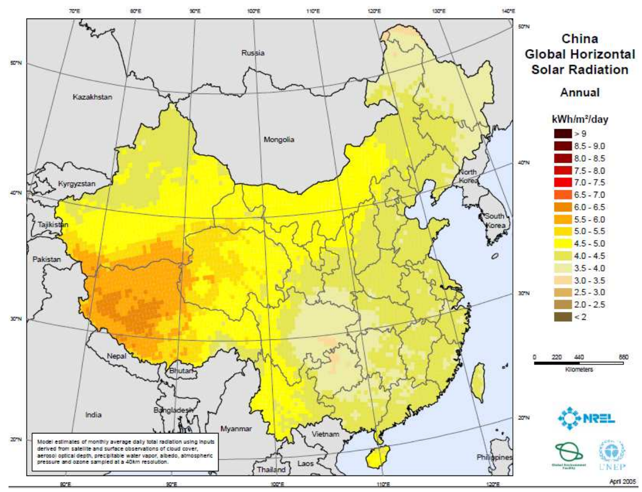


Fig. 1 China global horizontal solar radiation (Model estimates of monthly average daily total radiation using inputs derived from satellite and surface observations of cloud cover, aerosol optical depth, precipitable water vapor, albedo, atmospheric pressure and ozone sampled at a 40km resolution) [4].

However, the ecosystem of the northwest regions of China is very fragile. The forest coverage rate is low, and the vegetation was seriously degraded. Also the water supplies are constrained, the wind and sandstorms are severe, and the soil erosion problem is serious. See Fig. 2 and Fig. 3 for the

Chinese annual precipitation distribution and soil desertification to know the details. One question for the local, provincial, and national decision-makers is whether to and how to promote renewable electricity development in the face of a fragile ecosystem, and how to lessen the deterioration of environment. Thus, the environmental impacts of large-scale CSP (concentrated solar power) plants in Northwestern China deserve comprehensive research and understanding.

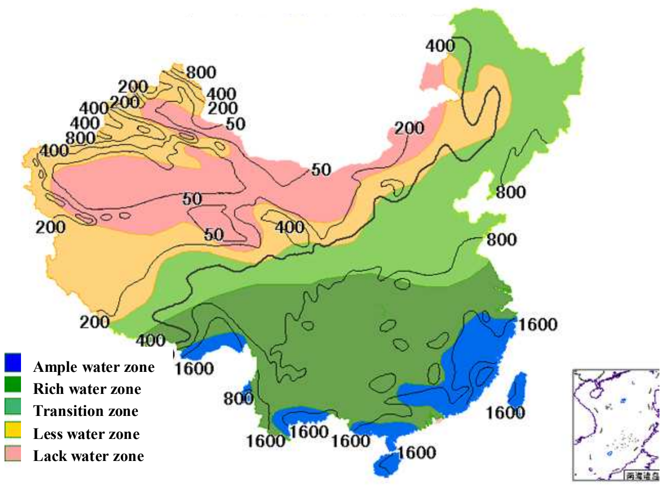


Fig. 2 Chinese annual precipitation distribution (mm/y)

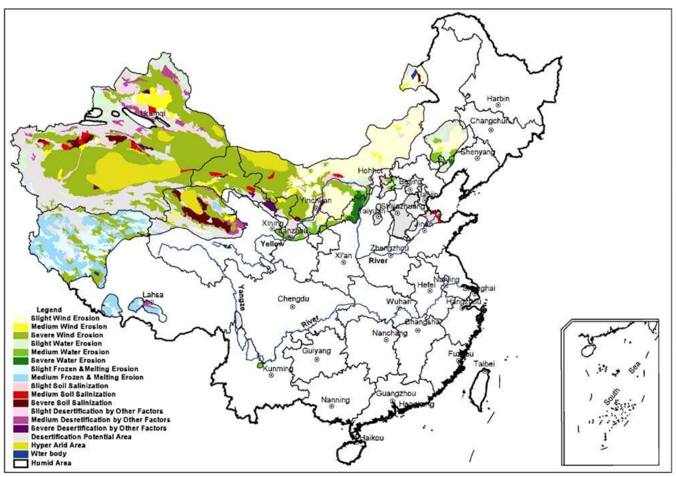


Fig. 3 Desertification distribution map in China [5]

The environmental impacts of CSP plants have been thoroughly studied in USA and Europe. The published literatures of the environmental impacts of solar energy utilization are mostly about the life cycle assessment of PV [6-8] and CSP [9-11] systems or components [12, 13]. Tsoutsos and Frantzeskaki [14] presents an overview of the environmental impact of solar energy technologies, and concluded the solar energy technologies present tremendous environmental benefits when compared with the conventional energy sources because of absence of almost any air emissions or waste products. From Tsoutsos's view, solar energy can be considered as an absolute clean and safe energy source. Turney and Fthenakis [15] systematically appraised the environmental impacts of large-scale solar power plants and found 22 of the considered 32 impacts to be beneficial. Of the remaining 10 impacts, 4 are neutral. However, Lovich and Ennen [16] investigated the potential effects of the construction and the eventual decommissioning of solar energy facilities, and concluded that the currently available peer-reviewed data is insufficient to allow a rigorous assessment of the impact of utility-scale solar energy development on wildlife. In the Californian desert region, the protection of desert tortoise and the construction of solar power plants has stirred intense debate [17, 18]. In addition, Keith et al. [19] investigated the hidden cost of electricity and pointed out that the cooling water use at CSP plants can be very high. Recently, Fthenakis and Kin [20] made a review study of the life-cycle uses of water in U.S. electricity generation. Hernandez et al. [21] analyzed the environmental impacts of utility-scale solar energy, and specificly pointed out the future research direction in this field. In China, the environmental impacts of solar power plant have aroused attention and discussion, but so far there are no published literatures about this.

In this study, the authors first introduced the characteristics of northwest regions of China, and stress the ecosystem there is fragile. Next the environmental impacts of the CSP plants on land use, human health and well-being, wildlife and wildlife habitat, noise and light is analyzed. Specifically, quantitative research is conducted on the soil erosion, water consumption and soil temperature of the CSP plant. The conclusion of this study is of great importance to the decision maker, regional plans and the development of CSP technology.

2. Characteristics of the northwest regions of China

2.1 Solar resources distribution in northwest China

According to estimation, the annually total solar radiation hitting China's land area is 5 x 10^{19} kilojoules (1.2 x 10^{19} kilocalories), equivalent to about 1700 billion tons of TCE (ton of standard coal equivalent). The annual sunlight hour ranges from 1000-3300. Over 60.1% of China's territory has an annual sunlight above 3000 hour, and annual irradiation above 5400 MJ/m^2 [22, 23].

The total solar energy resources are enormous in large area, but it is unevenly distributed in space. Fig. 1 shows the global horizontal solar radiation of China. Based on the distribution of the total radiation (note: the PV utilizes the total radiation, and CSP utilizes only the direct nominal radiation. Although there are differences between the total radiation and direct nominal radiation, but the PV panels and the reflector of CSP plants have similar influences on the environment) hitting China's land surface, it can be seen that Tibet, Qinghai, Xinjiang, the southern part of Inner Mongolia, Shanxi, northern Shaanxi, Hebei, Shandong, Liaoning, western Jilin, the middle and southwest parts of Yunnan, the southeast Guangdong, the southeast Fujian, the eastern and western parts of Hainan, and the southwest Taiwan all receive a relatively large amount of solar radiation. In particular, areas on the Qinghai-Tibetan Plateau receive the largest amounts of solar radiation all over China. According to the sunshine hours and solar total radiation, central Qinghai Province is regarded as the most abundant solar energy region.

2.2 Characteristics of the environment of northwest regions of China

(1) Low forest coverage rate

Northwest China belongs to the arid and semi-arid areas in the mid-temperate climate zone. The plentiful solar and heat resources, dry and strong evaporation, large temperature difference between day and night are the main climate features. There is low vegetation cover in most parts of northwest China. The capacities of vegetation to conserve soil water and to improve ecological environment are extremely weak. There are large areas of land desertification and dust storms in China. In the northwest region of China, the situation is especially bad (see Fig. 3). According to Ji [24], Xinjiang, Qinhai, Ningxia and Gansu have respectively forest cover rate of 0.79%, 0.35%, 1.54%, 4.33%.

(2) Strong wind and sandstorm

Chinese forest coverage has decreased remarkably during the past 4000 years, from 60% to 12.5%, and thus the desert area has increased rapidly, from 10% to 17. 6% [25]. Now some natural disasters, like strong wind and sandstorms often happened in the northwest China.
The northwest China has plentiful solar resource, and wind energy resource as well. In 2012, China had installed an astounding new wind energy capacity of 13.72 GW, and the cumulative wind energy capacity have reached at 70.21 GW by the end of 2012. The wind energy plants of China mostly locate at the northwest regions of China because of the reach wind energy there, especially in proviences of Xinjiang, Qinhai, and Gansu and inner Mongolia. According to the statistics, 62% area of northwest China have annual strong winds (refer to the wind has speed larger than 17 m/s, and the collector of CSP plant will stop under the strong wind) more than 50 days. In the regios of Ala mountain pass, the annual strong wind days are more than 160.
The sandstorms are usually caused by the wind. The wind is not a sufficient but precondition condition of the sandstorms. Thus, the interannual change and secular trend of sandstorms are partially consistent with the variation of wind. Zhou et al. [26] studied the characteristics of sandstorms in China, and concluded the arid and semi-arid regions in north part of China are sandstorm's easily influencing area, and northwest is high-incidence area. The frequency of sandstorms increased in Qinhai, Xinjiang and Inner Mongolia during the last 45 years. In addition, most regions at the west of longitude 110 ^{o} east and south of the Tianshan montain, the average annual sandstorm exceed 10 days, and even exceed 20 days in some parts within this region. In the path of the storm, sand and dust is floating in the sky, the air is polluted, traffic is blocked, and people find it difficult to breathe. When the sandstorms invade, the particles in the air can do great harm to people's health. For example, the huge sandstorm of 5 May 1993 killed a hundred people [27], and even reduced the visibility to zero in some towns. In the spring season, the Beijing people often wear gas masks to avoid dust and sand from the northwest regions of China.

(3) Water shortage

Reporters found that global warming has aggravated the crisis of water shortage in northwest China when they conducted investigations there. Experts also predict that the crisis of water shortage in the region might be more serious in the future for the current trend of climate change and human activities like economical and social development.
According to data provided by China Meteorological Administration, experts predict the mean temperature in northwest China might rise by 1.9 to 2.3℃ in the coming fifty years, which will probably result in the glacial area shrinks by 27% and small glaciers less than 2 square kilometers will disappear Meanwhile taking into account the continuous increase of water demand for production and living, the northwest area will need about 20 billion more cubic meters of water per year during 2010 to 2030 according to estimates.
Dong et al. [28] pointed out the "desertification" is the result of the global climate change and human activities in the semi-arid and dry sub-humid areas. Desertification is a process of environmental degradation, which can be mainly attributed to soil erosion because of wind. Furthermore, soil erosion occurs in the first place because of the destroying of vegetation.
The northwest of China has a huge solar resource, but the fragile ecological environment is a serious hamper to the solar utilization projects, such as CSP and PV plants.

3. Environmental impacts

3.1. Land use

PV and CSP electric systems are among the most efficient solar electricity technologies when it comes to land use because the collectors track and concentrate solar rays. The precise land needs of solar power plant depend on the plant's site, capacity and the used technology. Generally, a large piece of land is required for utility-scale solar power plants - approximately one square kilometer for every 20-60 megawatts (MW), and this is generally considered not a problem. There are two reasons for this standpoint. The first point is particularly advantageous as most solar energy abundant regions are located in arid and semi-arid zones, where the population density is small and thus the land is cheap. This is particularly true in the regions of China's northwest, where there is abundant solar resource and the population density is very small. Roughly less than 4% of the population live in the northwest where account for about 30% of the country's land area. The second is the lands that the CSP plant could be used for multi-purpose. For example, Goji berries were planted under the PV panels in the desert area in Ningxia Hui Autonomous Region, see Fig. 8. This would result in solar plants creating extra land rather than land "consumption". Because the collectors of CSP plants are often higher than the convectional PV panels, as a result there are more choices for multi-purpose land use.
David Mills, the chairman of the concentrating solar power (CSP) manufacturer Ausra, claims that 100 percent of the 2005/6 US electric power (1067 GW and a non-coincident peak load of 789 GW), day and night, could be supplied by 23,418 km^2 of CSP plant, or a square with 153 km sides [29]. Because China consumes approximately the same energy as the USA [30], a similar piece of land of solar power plants can produce a quantity of electricity consumed by China today, and this land area is equal to not more than 1 % of the whole Northwest of China.

3.2. Human health and well-being

The human health and well-being problems related to CSP plants are dependent on the adapted specific technology, because different technology will use different materials. First, the CSP plants overcome the intermittence of solar radiation by using hybrid designs or thermal storages. A hybrid CSP plant needs to burn fossil fuels, such as natural gas, coal or oil. The combustion of fossil fuels will emit pollution, such as NOx or CO and CO_2. These pollutants have well-known detrimental effects to the ecosystems, human health and well-being [31]. Second, the CSP plants usually use heat transfer fluid, such as synthetic oil, liquid sodium or molten salts. Although the heat transfer fluid are produced, distributed, stored, and consumed almost exclusively in closed systems, exposure can still occur in various facilities or phases of the CSP plants. The heat transfer fluids can volatile bad smells, and the accidental release of heat transfer fluids could form a health hazard. Furthermore the accidental spill of heat transfer fluid can pollute the soil and water. If a large spill does occur, the material should be contained, captured, collected, and reprocessed or disposed of according to applicable governmental requirements. Finally, the synthetic oil is flammable and unsteady at elevated temperatures. During a fire, smoke may contain toxic or irritating combustion products. Exposure to elevated temperatures can cause these products to decompose, with the possible release of traces of toxic materials. Moreover, since the land for CSP plants is mostly located in remote arid and semi-arid zones where there is usually a lack of accident protection infrastructure.

On the issue of light, central tower systems have the potential to concentrate light to intensities that could damage eyesight, or burn the birds if they fly close the focal point [21]. Under normal operating conditions this should not pose any danger to operators, but failure of tracking of the heliostat could result in straying beams that might pose an occupational safety risk on-site.

However, central tower systems with Brayton cycles are environmentally friendly because the used heat transfer fluids, for example the air [32] or CO_2 [33], are never detrimental to human health or environment and controllable within a large range of temperature and pressure.

3.3. Wildlife and habitat

The construction of large-scale solar power plant will change the appearance of local environment, on which the local flora and fauna rely on. The environmental impacts are different during the construction and operation phases. During the construction phase, the impacts are drastic. The construction machinery and transport vehicles will destroy most vegetation coverage and habitat, cause environmental vibration and noise, which will scare the fauna away. This is why the Ivanpah Solar Power project attracted some controversy because of it's location on desert habitat considered by wildlife officials and environmentalists to be important for the threatened desert tortoise [34]. During the operation phase, it takes time for the flora and fauna to adapt themselves to the new environment. For example, during the first year of operating a demonstration plant in Yanqing, Beijing, China, the technicians noticed that some birds hit on the collector and died because they can’t distinguish the direction when they meet the mirrors on the heliostat [21, 35]. However, after sometime the birds become adapted, and now this has changed. For example, some magpies build their nests on the heliostat, and the turkeys returned and forage in the undergrowth of the heliostat field.

In addition, the soil environment will be thoroughly changed because of the construction of basement and movement of the machinery and transport vehicles. The inherent biological soil crusts will be turn over and this will speedup the soil erosion, because it usually takes a long time to form the biological soil crusts.

On the other hand the shade created by the reflectors has a beneficial effect on the microclimate around the scheme and on the vegetation, too. Provided that such schemes are not deployed in ecologically sensitive areas or in areas of natural beauty, it is unlikely that any of the above changes would be considered as significant.

However, the concentrated solar radiation is sometimes a danger light. Concerning parabolic trough collectors, the parabolic trough collectors concentrate the solar radiation into a line, and this focal line could pose a danger to the nearby human and vegetation when the pitch angle is small. As for the central concentrator power systems, the concentrated solar radiation could pose a danger to the nearby human, vegetation, building and birds [35]. But operational experience shows that birds can positively avoid the danger areas after they adapt to new environments. Flying insects can also be burnt when flying close to the focus’s area. However, the effect on the insect population is unknown.

3.4. Water consumption

Water consumption is of course an issue with CSP plants because there is generally little water in these areas where the sun is most intense. Currently, there are four different CSP technologies: power tower, parabolic trough, linear Fresnel and dish Stirling. Simply put, a CSP plant is a conventional power plant using the sun’s heat as the energy source. Different CSP technologies consume different amount of water, and CSP plants with steam turbine require the most amount of water. CSP plants consume water in three different ways: wet cooling system, make up water (in the Rankine steam cycle) and mirror washing. As for the wet cooling, there are open loop and closed loop cooling. Consequently, the water consumption of CSP plants is difficult to calculate. Precise water consumption calculating of CSP plants depends on the adapted technology, and the site’s weather and environmental information.

In a CSP plants, the wet cooling (if it is used) consumes a substantial amount of water for the heat rejection in a similar way as do water-cooled fossil and nuclear plants. The water use is often measured by the produced electricity. How much electricity a CSP plant will generate in a year depends on the amount of time the plant operates. Arnold [36], Jordan [37] and Keith [19] predicted the parabolic trough plants will consume 2876–3483 L/MWhe, and power tower plants will consume a little bit less water. With the same wet cooling technology, the water consumption differences between different CSP plants are mainly contributed to the generated steam temperature, which is crucial to the heat-to-electricity conversion efficiency. In a recent study [38], a detailed water consumption prediction was conducted, in which the water evaporation, make up water, drift and blow down were considered. The results show the real water consumption maybe 20% more than the data in [19, 36, 37], and reachs at about 4000 L/MWhe. It also concluded that CSP using wet cooling (i.e., solar trough and solar tower) consumes more water per MWhe than some other generation technologies because the lower steam temperature, for example the produced steam temperature of parabolic trough plant is limited to 400 °C because higher temperature can cause HTF degradation [39].

If pure air cooling or air/water hybrid cooling technologies are used, the plants will save about 90% of water. However the equipment to provide air cooling is currently 3.3 times more expensive than that of wet cooling. As a result ,the cost of electricity is about 10% more expensive [40].

In addition, the build-up of dust and other deposits significantly increased reflection losses and thus reduced the overall efficiency of CSP plants. Therefore, the concentrators need periodic cleaning, which is usually done with water. Mirror cleaning is a maintenance requirement of CSP plant at the sites. However, mirror wash rates are subjective and mainly depend on the location of the concentrated solar power plants [41]. In the same study previously cited, an assumption of 0.6 liters of wash water per square meter of solar field and an annual wash interval of five days, or 73 washes per year has been done [40]. The same ratio is used for the analysis. This ratio is particularly high, but the best solar conditions for implementing solar thermal power plants are found in desert-sand regions of the world where dust and soiling are a significant problem. In these areas there is a lack of natural cleaning through rainfall or moisture [42].

Many solar power plants have already replaced manual methods by automatic washing mechanisms which are less labor-intensive, improve the washing quality and reduce the amount of water consumption. Novatec Solar, a German company, developed an automatic mirror-cleaner which uses about 98% less water than typical parabolic trough-cleaning systems.

Self-cleaning materials are also promising for the future of concentrated solar power plant and solar panels. The technology, initially developed with NASA for use in lunar and Mars missions, uses a transparent, electrically sensitive material, which is deposited on glass or a transparent plastic sheet covering the panels. Sensors measure dust levels on the panel surface and energize the material when dust concentration reaches a predetermined level. The electric charge transmits a dust-repelling wave over the material surface, lifting away dust and transporting it off the screen's edges.

According to the prediction in [38], a 50 MW parabolic trough power plant (steam temperature 390 °C, annual operation 8000 hours) in Gansu province will consume 1,600,000 m^3 of water (including the water evaporation, blow-down, mirror cleaning and drift) freshwater if using wet cooling technology, and 400,000 m^3 (including the water blow-down, mirror cleaning and drift) freshwater will be used if using air cooling. Subsequently the water consumption will be a big burden to the environment if large-scale CSP power plants are built in the northwest China in the future.

3.5. Soil erosion

In the northwest of China, there are inherent conditions for soil erosion, such as the dry climates, sandy soils and strong winds. Research has shown that historically, the deserts in the northwest of China were formed mainly because of the dry climate, deep sandy soil sand extensive human activities, for example the uncontrolled grazing, and mine exploitation. However, in recent years, the main causes affecting desertification are climate change and human activities [43-45]. The climate change refers to the global warming and extreme weather events et al. Human activities mainly refer to disafforestation, overgrazing and the exploiting of land for coal, ore or minerals et al.

According to the national soil erosion remote-sensing survey in 2000, 1.91 million km^2, which accounted for 20% of the total area in China, was affected by wind erosion [46], see Fig. 3. As a result of desertification during the 1990s, the Gobi, Tengger, and Ordos deserts had extended eastward into the semi-arid areas of Inner Mongolia [47]. In 2004, the total area of degraded steppe was about 7700 km^2, which was 82% of the total steppe area of the Xilin catchment [48]. This dramatic change was caused mainly by improper utilization of land [49, 50].

Within the collector fields, the soil environment will be drastically changed because of the construction of CSP plants. The soil near the collector fields will also be disturbed because of the activities of machinery and vehicles. The vegetation coverage and inherent biological soil crusts will be destroyed. The sand in the soil will get loose and thus will be more prone to erosion. Consequently, soil erosion will increase during the construction phase.

However, the collector fields of CSP plants will most certainly affect the wind environment, especially the atmosphere boundary layer. Like the water consumption characteristics, different concentrators will have different influences on the wind environment. In this study, the influences of parabolic trough collector field on the wind environment were investigated. Because the parabolic trough collector has structurally regular shape and the collector field has a regular layout, and the parabolic trough solar technology is the most mature and widely-applied solar thermal power technology today.

As discussed previously wind is the main natural force of the desertification, which plays a key role in forming the surface features of desertification. The wind environment in parabolic trough field was numerically studied in this study. The computational domain consists of six rows of collector, see Fig. 4. The investigation was done by solving the three dimensional Navier–Stokes equations. A detached-eddy simulation [51] technique was used to predict the flow field because there are massively separated and recirculation flows within the collector field.

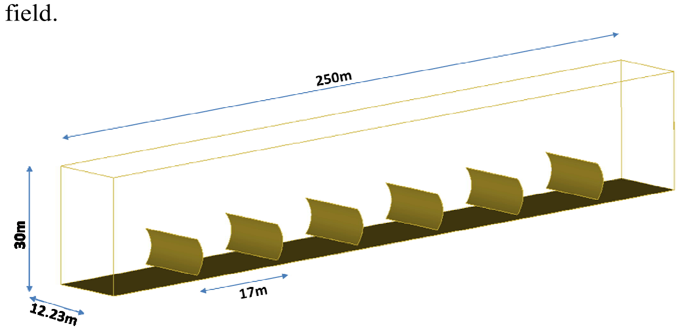
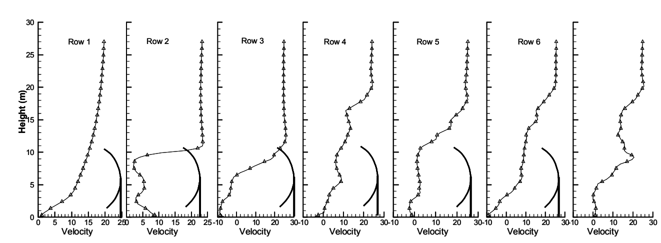


Fig. 4 The studied parabolic trough collector Field

Fig. 5 presents the instantaneous velocity and turbulent energy profiles within the studied parabolic trough collector field, it shows the air flow inside the parabolic trough fields is very turbulent.



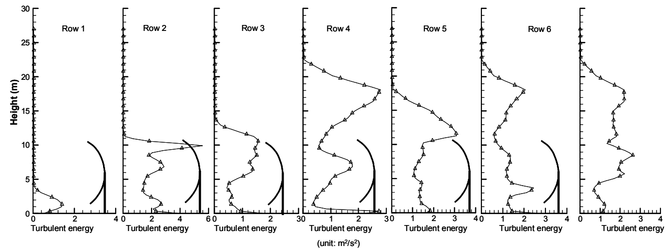


Fig. 5 Instantaneous Velocity and Turbulent Profiles Within parabolic trough collector Field

Fig. 6 presents the mean velocity and turbulent profiles within parabolic trough collector field. It shows the mean velocity decreases dramatically and the turbulence kinetic energy increases within the collector fields. The decrease of velocity is of greatly beneficial, because the wind speed was of primary importance to the soil wind erosion [52, 53]. According to the experimental results in [54], the threshold wind velocities for sand movement is about 10 m/s (at the height of 2 m). Fig. 7 presents the instantaneous velocity distribution, it is obvious that the velocity within the collector fields decrease, and there exists massive recirculation flow. From **Error! Reference source not found.**, Fig. 6 and Fig. 7, it is clear the wind speed inside the collector field is lower than the threshold velocity in [54, 55].

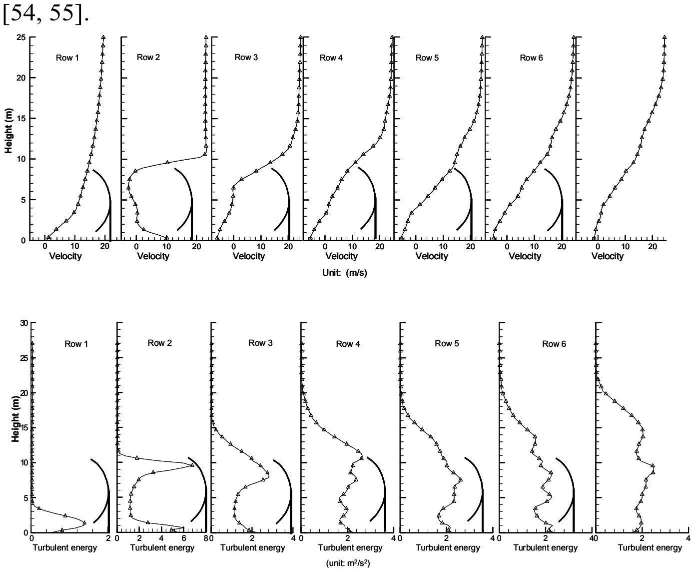


Fig. 6 Mean Velocity and Turbulent Energy Profiles Within parabolic trough collector Field

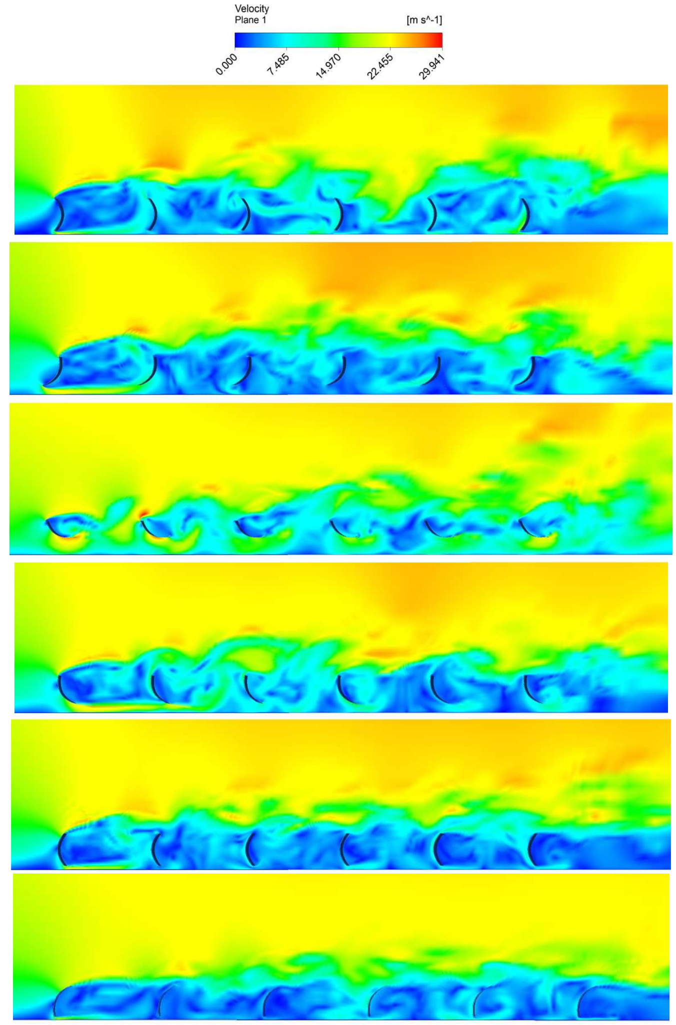


Fig. 7 Flow field within the parabolic trough collector Field

Although the wind direction is almost at random in reality, the studied collector orientations and wind directions are limited, and the soil erosion is dependent on the sands size, the cloddiness of sands, and the wind velocity itself, the authors can still conclude from the wind flow fields inside the collector field the existence of parabolic trough collector field is in favor of soil protection. For example, the PV panels can protect the soil from erosion, and the land which once was desert can be used to plant trees.. Fig. 8 shows the trees, PV panel and Goji berries co-exists in Tengger Desert near Zhongwei, Ningxia Hui autonomous region.

Fig. 8 Integrated utilization of land.

(PV panels, Goji berries and trees exist together. Zhongwei, Ningxia, China)

3.6. Soil temperature

Soil temperature critically affects agriculture by impacting crop's abilities to produce their own nutrients. This in turn can boost or stymie plant growth, pollination, and production of fruit as simultaneously when soil temperature climbs and gets warmer, the plant will also realize a boost in respiration. This in turn increases demand for photosynthesis with sun light as plants need to produce energy to keep up with the respiration demand. The inverse occurs when plant soil gets colder.

The existing of concentrator collectors interdicts the sunlight, and creates intermittent shading on the land. This has broken the energy balances of soil, and it will have a significant impact on the soil temperature. Marrow conducted detailed studies [56, 57] of the agrivoltaic system which is "mixed systems associating solar panels and crop at the same time on the same land", and concluded the light reduction had a significant impact on final crop yield of spring and summer lettuces. In addition, they noticed a significant delay in flowering date. Although the suitable land for solar utilization in northwest China is mostly semi-arid and dry sub-humid areas and the impacts on crop is not a main concern, the soil temperature will have impacts on the atmosphere, depletion of soil organic matter [58] and soil properties [59]. In this study, the impact of the reflector on soil temperature was experimentally studied.

Data was collected on an experimental site (see Fig. 9), in Yanqing (40.47◦ N; 115.97◦ E), Beijing, Chins from August 2010 to October 2013, and the measurement time-step was one hour. The aim of this study is to investigate the effect of intermittent shading on soil temperature, and thus an experimental device was designed as Fig.12. The 5 rows of opaque flat board were held at 1.2 m aboveground by pillars. The board size is 20 m×1.2m, and the space between rows is 5.6 m. 20 thermocouples (5 points, see the black points in Fig. 9. For each location 4 thermocouples were installed at points of depth 5 cm, 20 cm, 65 cm and 100 cm). To eliminate the border effect, the thermocouples were placed in the middle. For comparison, 5 thermocouples were placed outside of the structure where there was no shading. In order to eliminate factors (sensor and transmitter drift and non-linearities, limited sensor calibration precision) that typically affect the quality of small temperature difference data, the sensors are calibrated relative to one another. In doing so, an agreement of the sensors and their entire measurement chain to about 1.0 K is obtained.

In fact, several soil moisture sensors were also installed because soil moisture affects the wind soil erosion [60]. However, it was not discussed in this study. The reason is the measured data show the soil moisture is not distinguishable either because of the low accuracy of the sensors or the impact of the shading on the humidity of soil is small.

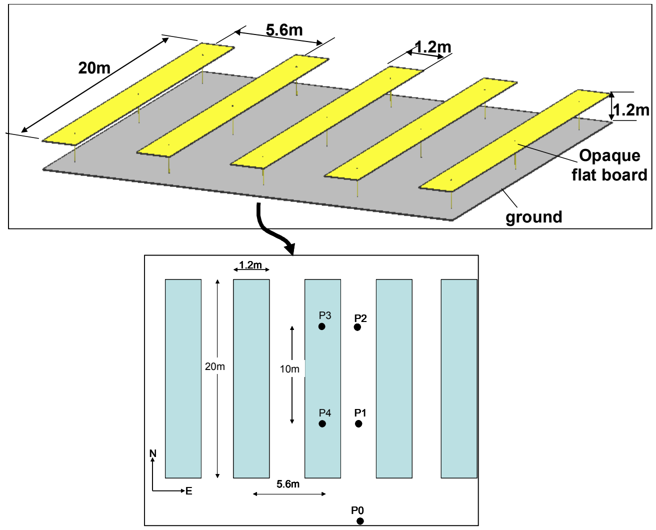


Fig. 9 General map of the experimental device. The top frame is the perspective view; the bottom frame is the planform. Black circles represent locations of sensors

Fig. 10 presents the measured average daily temperature during one year. To avoid the boundary effects, the measured data of similar locations (P2 and P1, P3 and P4. See Fig. 9) were further averaged. Fig. 10 (a) and Fig. 10 (c) shows the existing of structure can cause the soil temperature at 0.5-4 °C higher than the soil without the structure. The authors contribute this phenomenon to the atmospheric movement, during the winter period the air has a lower temperature than the soil. The air will absorb heat from the soil when the air temperature is lower than the soil temperature, and vice versa, the air will release heat to the soil. Therefore, the soil where has a lower atmospheric movement speed will receive a smaller impact. Although the designed experimental device is different with the parabolic trough collector in section 3.5, the study has shown the air speed will decrease because of the shading structure. In Fig. 10 (b) shows the existing of experimental device can cause the soil temperature at 0.5-4 °C lower than the soil where is not the structure. The authors contribute this phenomenon to the sunlight radiation, while the shading structure intercepts the sunlight.

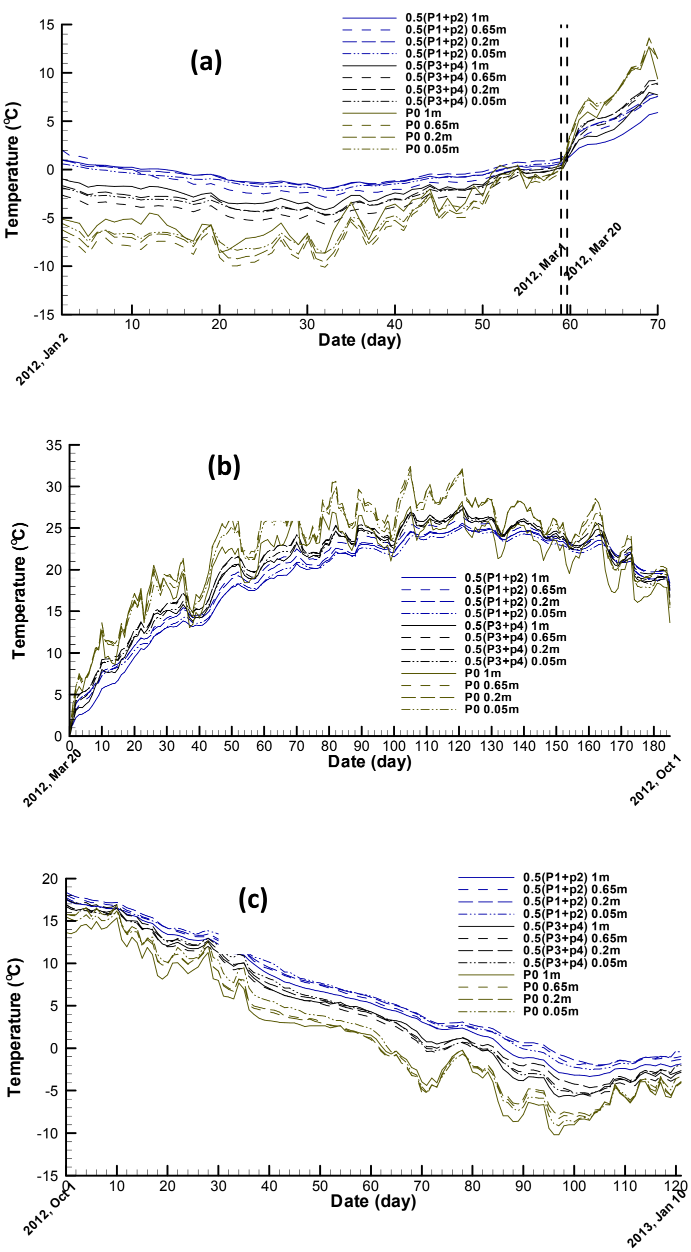


Fig. 10 The measured average daily temperature variation curves at different locations. (a) From Jan 2 to Mar 20; (b) From Mar 20 to Oct 1; (c) From Oct 1 2 to Jan 10

In addition, Fig. 10 also shows the change magnitudes of daily soil temperature are different. Position P0 has the biggest change, position P1 and P2 have the moderate, and P1 and P2 have the least change magnitude of daily soil temperature. The authors contribute this to the existing of experimental device, which baffles the atmospheric movement.

4. Conclusions

In this study, we identified and appraised the environmental impacts of large-scale solar power plants. For the large-scale solar power plants in Northwestern China, the following conclusions can be made:

(i) Land use is not a problem for solar energy utilization;

(ii) CSP power plants will do no harm to the human health and well-being;

(iii) CSP power plants have impacts on the wildlife and habitat. However the impacts are temporary and not significant.

(iv) During the construction stage, the CSP power plants will result in huge impacts to the local environment, especially the soil.

(V) The water consumption of CSP power plants depends on the adapted technologies, mainly on the steam temperature and cooling technology. According to the study, a 50 MW parabolic trough power plant (steam temperature 390 °C, annual operating hour 8000) in Gansu province will consume 1,600,000 m^3 (including the water evaporation, blow-down, mirror cleaning and drift) freshwater if using wet cooling, and 400000 m^3 if use dry cooling technology.

(VI) Large-scale solar power plants in Northwestern China will bring detrimental impact to soil erosion during the construction phase, and beneficial impact during the operational stage.

(VII) The presence of collectors of CSP plants will cause a 0.5-4 °C impact to the soil environment. At wintertime, the soil temperature will be 0.5-4 °C higher than the soil outside the collector fields. However, at spring and summer season, the soil temperature will be 0.5-4 °C lower than the soil outside the collector fields.

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Notes and references

[a]Key Laboratory of Solar Thermal Energy and Photovoltaic System, Institute of Electrical Engineering, Chinese Academy of Sciences, No. 6 Beiertiao, Zhongguancun, Beijing 100190, China

[b]School of Energy and Power Engineering, Beihang University, Beijing 100191, China

[c]Huadian Engineering, Co, Beijing 100190, China

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