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Forum article

Great wall of solar panels to mitigate yellow dust storm

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ABSTRACT

Mitigation of the large scale yellow dust storm is a serious problem facing China. We propose the approach of building windbreak walls equipped with solar panels in the proximity of dust origins. The solar panels generate electricity in the sunny days; the walls break the wind and remove airborne dusts based on the impactor principle during wind storms. Preliminary calculation indicates the walls may be able to remove the major fraction of the airborne dusts and the generated electricity could be significant. More detailed studies are needed to prove the feasibility of the approach.

1. Introduction

China and adjacent countries have suffered disastrous economical losses caused by large scale yellow dust storms in recent years. The negative impacts to the ecological systems and public health are likely to be significant and may manifest themselves in the years to come. For instance, the dust and sandstorm on 5 May 1993 in the Hexi corridor of Gansu Province in western China directly affected 1.1 million square kilometers and resulted in 85 dead, 246 injured, 4412 houses destroyed, 120,000 livestock dead or lost and 373,000 hectares of crop land damaged. The direct economic cost of this dust and sandstorm in China alone was more than 550 million yuan RMB (UN, 2004). Lu and Wu (2002) estimated that some 400 million people were affected by dust-sand storms and desertification in China. The annual direct economic losses attributable to desertification were estimated at 64.2 billion yuan RMB, which was equivalent to US$7.7 billion at the exchange rate of 2002. It was believed that the indirect economic losses arising from desertification mount to 288.9 billion yuan per year (Lu & Wu, 2002).

The air quality in China has become an issue of focus, with the regular measurement of $PM_{2.5}$ and PM_{10} published by the national meteorological administration offices revealing significant air quality problems in many cities of China. The yellow dust storms carry enormous amount of airborne dust particles, and can drastically change the PM_{10} level. For instance, the two severe dust storms in March and April 2002 swept across Mongolia and hit 18 provinces in China, the Korean Peninsula, and a large area of Japan. Total suspended particulate levels in the affected areas were 10–100 times higher than the national standards in these countries (UN, 2004). The World Health Organization (WHO) in its guideline for protection of health (WHO, 2006) proposed 50 $\mu g/m^3$ as the maximum daily mean value of PM_{10}. Wang et al. (2011) cited Chinese PM_{10} statistical data and meteorological observations, and provided the following correlation for dust storm events: PM_{10} average concentration is 2396 $\mu g/m^3$ (range 656–8490 $\mu g/m^3$) in the dust storm origin regions; PM_{10} average concentration is 1766 $\mu g/m^3$ (range 823–2571 $\mu g/m^3$) in the dust storm affected regions. Clearly these values are vastly higher than the WHO guidelines. A number of studies examined the health impact of dust storms. Though some studies concluded that episodes of high coarse particle concentrations are not associated with increased mortality (Schwartz et al., 1999), others reported adverse health impact and correlated the daily mortality to Asian dust storm events (Chen et al., 2004; Kwon, Cho, Chun, Lagarde, & Pershagen, 2002; Wang et al., 2011) or Saharan dust (Jiménez, Linares, Martínez, & Díaz, 2010; Perez et al., 2008).

The origins of the dust storms affecting China have been extensively studied (Prospero, Ginoux, Torres, Nicholson, & Gill, 2002; Shao & Dong, 2006; Sun, Zhang, & Liu, 2001; Wang, Xia, Wang, Xue, & Li, 2008; Washington, Todd, Middleton, & Goudie, 2003; Zhou, 2001). It is believed that the dominant source regions for Asian

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dust are the Gobi and the Taklamakan Deserts and alluvial fans adjacent to Gobi deserts in the piedmonts of the Kunlun, Qilian, Helan, and Gobi Altai mountains. The dust storm starts when high wind lifts some dust particles at the origin and when the dust particles fall, they cause more dust particles to become airborne. This "saltation" process repeats until an avalanche of dust storm occurs downstream.

The main techniques to prevent desertification include shelterbelt, dune-building grass (Pye & Tsoar, 2009), sand fences (Pye & Tsoar, 2009; Wilson, 2004), wind-break walls (Bouvet, Wilson, & Tuzet, 2006), cementing material and plastic mulching (UN, 2004), straw checkerboard barriers (Huang, Huang, Chen, Hsu, & Li, 2013; Huang, Xia, & Tong, 2013; Zheng, 2009), etc. China embarked on the programmatic approach in 1978, marked by the "Three-North" (Northeast, North, and Northwest China) Shelterbelt Program, which is also known as the "Great Green Wall". Significant results have been achieved in that the forest cover of the "Three North" region has increased to 6.06% in the early 2000s from the 5.05% of the late 1970s (Lu & Wu, 2002). China's strategies include engineering approaches such as building windbreaks on the peripheries of deserts, safeguarding the outskirts of cities and towns, protecting river headwaters (Lu & Wu, 2002), runoff afforestation (UN, 2004), and socio-economic approaches such as adoption of integrated and sustainable land management practices (UN, 2004), protecting oases, managing agro-pastoral transition zones (Lu & Wu, 2002).

In the foreseeable future, environmental protection and energy management are two critical issues facing the society. In this study, we propose an approach combining windbreaks and solar panels in an attempt to mitigate the yellow dust storm and to harness the solar energy. In analogy to the "Great Green Wall", we call this approach the "Great Walls of Solar Panels".

2. The approach of windbreak walls of solar panels

The heart of the proposed approach is to erect a series of windbreak walls equipped with solar panels in the proximity of dust origins. These walls comprise of sections mounted on shafts which can rotate under the control of a central station, as illustrated in Fig. 1. Solar panels are mounted on one side the wall; stainless steel or similar material covers the other side of the wall. On sunny days (most of the time in the arid area), the walls are close to horizontal orientation with the solar panels facing the sunshine (Fig. 1(a)). The shafts can rotate to achieve the angle of the maximum incident sunshine intensity on the solar panels. The generated electricity can be used to powder nearby towns. When there is warning of a dust storm, the panels rotate so that the back side of stainless steel faces the dust storm (Fig. 1(b)). The back panels then serve as impactors; the large and heavy dust particles impact on them, lose velocity in the wind direction, and finally drop on the ground due to gravity. The windbreak walls may disrupt the dust movement sufficiently to stop the dust storm to form and protect the downstream towns.

The capability of filtering windborne particles by windbreak walls has been studied before (Bouvet et al., 2006; Bouvet, Loubet, Wilson, & Tuzet, 2007; Raupach, Woods, Dorr, Leys, & Cleugh, 2001). These studies focused on conditions similar to natural windbreaks such as hedges or tree rows, which have relatively low height (1–15 m) and considerable porosity. Bouvet et al. (2007) stated that a sizeable fraction of the particle flux entering the shelterbelt across its upstream face is lifted out of its volume by the mean updraft induced by the deceleration of the flow in the near-upstream and entry region, and these particles thereby escape deposition in the windbreak. In our proposed approach, the walls can be built much taller, which can limit the updraft carrying particles over the top of the wall. There exist gaps between sections of the wall, which provide certain porosity and allow the wind to penetrate the wall. The particles with large inertia cannot follow the curling streamlines into the gaps, hit the wall, lose their velocity, and eventually drop on the ground. Thus the walls we propose operate like impactors to remove particles based on their inertia (Golovin & Putnam, 1962; Marple, Olsen, & Rubow, 2001).

Large amount of dusts are expected to accumulate on the ground near the base of the walls. To prevent these dusts from becoming airborne again, straw checkerboard barriers may be inserted to the ground near the walls to stabilize the accumulated dusts. After the wind storm, trucks can be used to transport the accumulated dusts away for possible usage as landscaping materials, building materials, sandbags, abrasive agents, etc.

3. Discussion

3.1. The airborne dust during dust storm event

Mori, Nishikawa, Tanimura, and Quan (2003) measured aerosols in China and Japan along the route of the dust event in March 2001. They reported that the mass concentration of the total suspended particles (TSP) was 6700 $\mu g/m^3$ in the Chinese interior (in and around the Inner Mongolia Autonomous Region) and 1500 $\mu g/m^3$

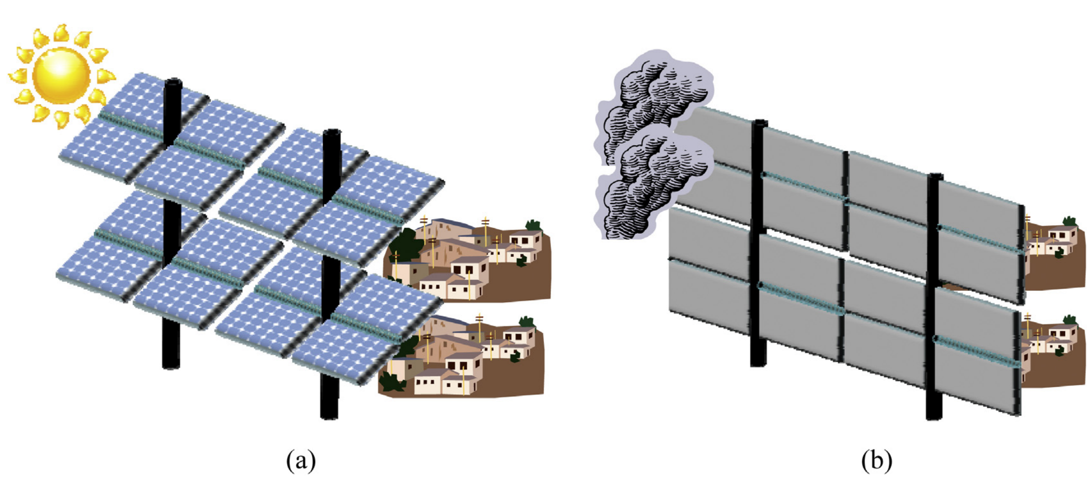

Fig. 1. Illustration of the approach of wind-break walls equipped with solar panels: (a) operation with the solar panels facing the sun; (b) operation with the back side facing the wind storm.

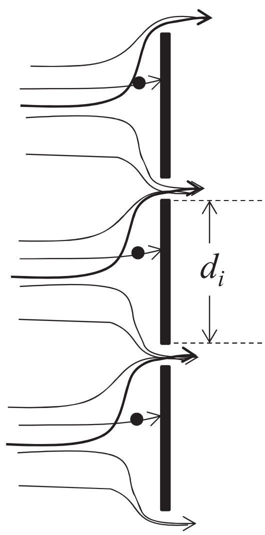

Fig. 2. A schematic of the wind going through several impactors and large particles being removed by the impactors.

at Beijing. The particle mass distribution in Beijing had one major peak in the size range of 4.7–7.0 μm. 93% of the total mass originated from coarse particles larger than 2.1 μm in aerodynamic diameter. These results are consistent with the PM_{10} average concentrations listed in Wang et al. (2011): 2396 μg/m^3 (range 656–8490 μg/m^3) in the dust storm origin region; 1766 μg/m^3 (range 823–2571 μg/m^3) in the dust storm affected region.

3.2. The impactor efficiency

The wall of solar panels operates like a collection of impactors. The efficiency of dust removal depends on the particle inertia and impactor size. The impactors fall in the ribbon impactor category, and the efficiency is defined as the fraction of the removed particles from the volume of the air swept out by the impactor body (Marple et al., 2001). The governing parameter of impaction is the particle Stokes number

$$Stk = \frac{\rho_p d_p^2 C_c U}{18 \mu d_i}, \tag{1}$$

where ρ_p is the particle density, d_p is the particle diameter, C_c is the Cunningham slip factor, U is the wind velocity, μ is the air viscosity, and d_i is the impactor size (Fig. 2). We assume that the dust density can be represented by the quartz density 2.6 g/cm^3. The near surface wind speed in a dust storm could reach 35 m/s (Shao & Dong, 2006) and it is a function of the distance to the ground. We use 15 m/s for estimation. The cutoff Stokes number is usually represented by Stk_{50}, which is the Stokes number at which 50% of the particles are removed by the impactor. According to Golovin and Putnam (1962), $Stk_{50} \approx 0.3$ for ribbon impactors. In the following table we list the cutoff particle sizes corresponding to Stk_{50} for different impactor sizes d_i (Table 1).

We can see that if the impactors have a side width of 5 cm, then 50% of 11 μm dust particles can be removed. For larger particles, the removal efficiency is higher and for smaller particles the removal efficiency is lower. If higher removal efficiency is desired, smaller d_i may be used; however, the size may be limited by the solar panel size. The impactors can be implemented in the form of slits or holes through the solar panels.

Table 1
The cutoff particle sizes corresponding to Stk_{50} for different impactor sizes d_i.

d_i (cm)	0.1	0.5	1	5
d_p (μm)	1.51	3.5	5	11.2
Stk	0.301	0.306	0.309	0.304

In addition to the volume of the air swept out by the impactor body, there is air volume which flows straight through the gaps between the impactors (Fig. 2). A large fraction of the particles in this part of the air volume can penetrate through the wall. Both the impactors and the gaps need to be considered for the overall removal efficiency of the wall. A series of walls in the wind direction may be used to improve the total removal efficiency, as the total penetration is subject to exponential decay with the number of walls in the wind direction.

3.3. The drag force on the wall

The drag force per unit length (N/m) due to the wind on the wall can be calculated as

$$F = \int_0^H \frac{\rho_a C_d U^2}{2} dz, \tag{2}$$

where ρ_a is the air density, C_d is the two dimensional drag coefficient of the impactor, H is the height of the wall and z is the vertical distance from the ground. U is a function of z and C_d depends on U. For a first estimation, we assume that the drag can be computed with a representative wind speed U = 15 m/s. The Reynolds number

$$Re = \frac{\rho_a d_i U}{\mu}, \tag{3}$$

is about 10^4 if d_i = 1 cm. We use the approximate value of $C_d \approx 2$ for an isolated flat plate (Anderson, 2001, p. 62), which should overestimate the drag. The drag force per unit length is then 270H N/m. If the wall height is 100 m, $F = 2.7 \times 10^4$ N/m. The pole that supports the wall on the ground thus needs to withstand significant force and torque.

3.4. The electricity generation

The conversion efficiency of commercial solar panels has increased over the years and is around 15–19% (Huang, Huang, et al., 2013; Huang, Xia, et al., 2013). We assume that the solar panels have 15% conversion efficiency and the power density from the sun is 1 kW/m^2, then the energy output of one square meter solar panel is 0.15 kW. The energy output can be compared to that from wind turbines. A large wind turbine can be 100 m tall with turbine diameter of 80 m and generate about 2.5 MW electricity (Gasch & Twele, 2012, p. 1). It is reasonable to compare such a wind turbine with a solar panel of 10,000 m^2 surface area. The energy output for a 10,000 m^2 solar panel is 1.5 MW, comparable to the large wind turbine. If we assume that the wall of solar panels is 100 m tall and ignore the gaps between panels, then each kilometer of the solar panel wall has 100,000 m^2 surface area. If 100 km of the wall is built, the total electricity generated would be 1500 MW. The annually averaged household electricity consumption is distributed mainly from about 400–2000 kWh, according to the survey data in the urban area of Sichuan province from 2007 to 2009 (Zhou & Teng, 2013). We use the value 1000 kWh per year per household for estimation. Assuming that the sunshine intensity on the solar panel walls is equivalent to 1 kW/m^2 for 200 days, 8 h per day annually, the electricity generated by 100 km of the wall would be sufficient to power 2.4 million households. The energy would help the nearby towns to prosper which can trigger further socio-economic changes such as poverty reduction, adoption of integrated and sustainable land management practices, that will further minimize the dust storm formation possibility in the future.

3.5. The possible locations for the walls of solar panels

The walls of solar panels may be erected at the edges of Gobi deserts, with some nearby towns so that the generated electricity can be effectively utilized. Some possible locations include: the east edge of the Tarim basin, near the Ruoqiang County of Xinjiang; the east edge of the Hexi Corridor, near the Minqin County of Gansu; south east of the Gobi Altai mountains, near the Urad Zhongqi in Inner Mongolia.

4. Summary

We outlined the approach of using windbreak walls equipped with solar panels to mitigate the yellow dust storm in China. The solar panels generate electricity in the sunny days; the walls break the wind and remove airborne dust during wind storms. Preliminary consideration of the dust removal efficiency, drag force, electricity production, and locations of the walls are discussed. If successful, the Great Walls of Solar Panels can reduce the possibility of dust storm inception and provide significant energy for nearby towns. It should be noted that we have not considered many important factors, such as the limits posed by solar panels, operability of solar panels under harsh conditions, the local weather and geomorphological conditions, electricity storage and transportation, financial aspects, etc. More detailed studies are needed to prove the feasibility of the approach.

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This article is a memorial to Prof. Daniel Joseph, Department of Aerospace Engineering and Mechanics, University of Minnesota, who passionately lectured in China, participated and contributed regularly in the dust storm seminars in China.

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One comment

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This paper presents a proposal, in which it proposes to build windbreak walls equipped with solar panels in the proximity of dust origins to mitigate large scale dust storms. Strong dust storms often occur not only nearby the desert region, but also spread out to a large region in northern China, including some large cities in northeastern China, such as Beijing, the capital city of China. Because there are serious haze events occurred in northeastern China, the dust storms cause the enhancement of the heavy haze events (both for their occurrence and magnitude).

The main concept of this proposal is to build a large wall nearby the Gobi Desert region, with double side of panels (one side of panel

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is solar panel, and another side is made of metal which can resist the momentum of the dust particles). The proposed method is clearly stated in the paper. Because this proposal is a geo-engineering method for air pollution control, several important issues, such as economical feasibility, uncertainty, and positive and negative effects, need to be carefully assessed and discussed. In order to assess the potential impact of the proposed windbreak wall on dust storms, a schematic picture is illustrated in the following pictures (panels in Fig. 1). The figure suggests that the dust storms have two outflows. One is nearby the windbreak wall, which have strong impacts on the nearby regions of deserts. Another one is an upper outflow of dust storms, which is produced by weather cyclone (see panels A and B). Because weather cyclone has a strong upward motion, the dust outflow can be at the altitude of several kilometers (see panel C), as a result, dust can be transported to a long distant in the downwind region (such as from Gobi to Beijing). In Fig. 1, it clearly shows that the proposed solar panel wall could play important roles to reduce the dust impacts close to desert regions, but have very minor impacts on the long distant in the downwind regions.

In summary, the proposed solar panel wall could have positive effects on the impacts of dust storms in close proximity to the desert region for improving the environment and for providing electrical power supply. However, it might not have significant impacts on the haze events occurred in the northeastern China.

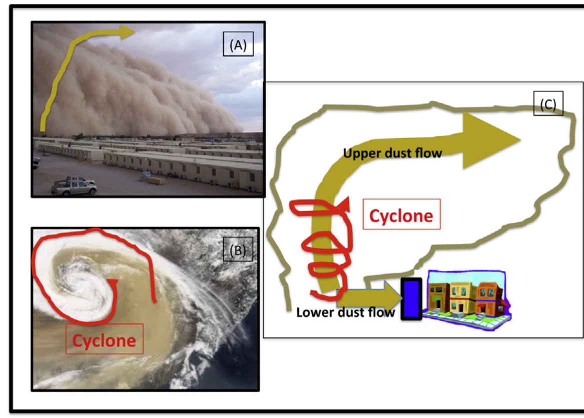

Fig. 1. A schematic illustration of the effect of dust storms on regions close to desert and long distant downstream.

Reply to the comment

David Y.H. Pui, Junji Cao, Zhisheng An, Jing Wang

We are grateful for the experts' comments on our manuscript. We fully understand the experts' concerns on the feasibility of the proposed idea of building windbreak walls equipped with solar panels to mitigate the yellow dust storm. As stated in the manuscript, we have not considered many important factors, such as the limits posed by solar panels, operability of solar panels under harsh conditions, the local weather and geomorphological conditions, electricity storage and transportation, financial aspects, etc. However, the manuscript is intended to present a Big Idea to stimulate more interesting ideas to solve Big Problems.

We fully agree that more detailed studies are needed to prove the feasibility of the proposed approach. A life cycle and cost assessment should form the framework of such studies, in which comparative analyses for various possible approaches to mitigate dust storms are performed (Curran, 2012). For example, the already implemented "Great Green Wall" approach can be used for comparison. The comparison parameters include the efficiency of dust reduction, effect on green house gas concentration, terrestrial acidification, water consumption, land-use footprint, initial investment, maintenance costs, energy balance, and others. Among the abovementioned parameters, the dust-reduction efficiency of the solar panel wall is not known. Both numerical and experimental studies can be carried out to estimate the efficiency. Fluid mechanics simulation has been used to study wind-breaking fences and barriers (Patton, Shaw, Judd, & Raupach, 1998; Wilson, 2004; Zheng, 2009; Huang, Xia, & Tong, 2013), and can be extended for the solar panel wall. Wind tunnel experiments (Lee, Park, & Park, 2002; Zhang, Kang, & Lee, 2010) using properly designed fences, air flow conditions and particles can be used to investigate the efficiency of the solar panel wall. The comparative assessment will illustrate the advantages and disadvantages of the approach and facilitate further discussion.

One of the experts raised a question regarding the cyclone wind effect, which lifts dust to high altitude and leads to long range transfer. All types of wind-breaking walls have finite height and limited effects on dust at high altitude. Strategic arrangement of the walls, e.g. deployment of the walls near the origin of the dust storm, would improve the efficiency. In this regard our approach has the advantage over traditional tree shelterbelt in that the height of the solar panel wall can be designed based on the wind condition.

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