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The linear mirror for solar energy exploitation

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Summary. — We describe a simple two-dimensional array of plane mirrors operated by only two motors, which collects efficiently Sun light in order to produce electrical power at about the cost of oil. The system preserves the merits of previous state-of-the-art solar power plants but is simpler and by far less expensive. A first prototype has been operated at the Physics Department of the University of Udine providing a power of 0.56 kW per m^2 of mirror surface in mid November.

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1. – State of the art

Nowadays there are several quite different techniques for exploiting solar energy. Solar panels can be used for heating water. In winter at European latitudes these panels can heat water up to about 60 °C [1]. Electricity can be obtained from semiconducting photovoltaic modules. Both these technologies are rather expensive. The cost of the photovoltaic panel is typically 700 euro/(m^2 of radiated area) [2], resulting in a price of about 40 to 50 cent/kWh.

One can exploit solar energy by means of concentrating mirror systems [3]. They can provide heat at relatively high temperatures (up to about 1000 °C) and generate hot steam driving a turbine to produce electricity. At the same time they provide lower temperature heat—that can be used for instance for heating buildings. However, existing mirror systems suitably concentrating solar light are even more expensive than solar panels or photovoltaic modules. In addition, their operation is rather complex. As a consequence their use up to now has been very limited [4].

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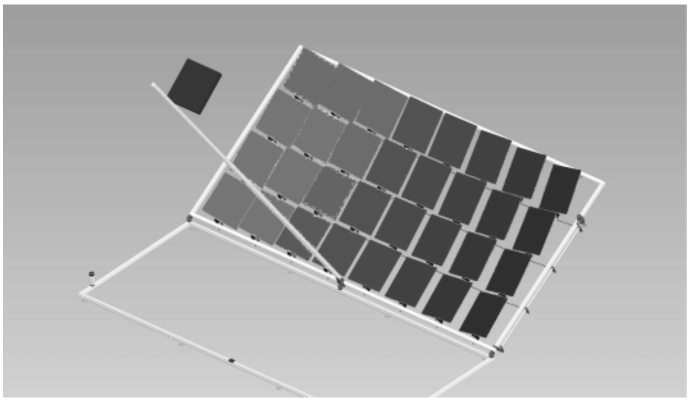

Fig. 1. – Pictorial view of a matrix of mirrors, reflecting Sun light onto a focal area.

There are various ways of realizing a concentrating mirror system:

1) Parabolic mirrors focus parallel Sun rays onto a common focal point. The advantage of parabolic mirrors is the simplicity of the system to control their motion—the mirror simply has to point to the Sun. Their problem is the construction of the parabola. Large parabolic mirrors are particularly expensive [5].

2) Parabolic "trough" systems are only particular versions of the parabolic mirror.

3) Solar towers consist in an array of planar mirrors, each reflecting the Sun rays onto an approximate focal point at the top of a tower. These systems are relatively easy to construct. However, their control system is very complex, the motion of each mirror being driven by two precision motors. This results again in a high system price.

In this paper we describe a mirror system similar to a solar tower which allows exploiting solar energy at a much lower cost. A pictorial view of such an array is shown in fig. 1.

2. – The linear mirror

The linear mirror depicted in fig. 1 consists of four rows of mirrors, arranged in a matrix, and a focal area which collects the concentrated sunlight during the day. The system is oriented so that the focal area points toward the South.

In order to illustrate the principle of functioning([1]) of this system, we begin considering one of the four rows of the mirror matrix. The mirrors are mounted on axes which form a plane normal to the incident Sun rays. We denote the orientation of each mirror by means of the normal to its surface. This vector is referred to as "mirror vector" in the following. This system is sketched as viewed along the axes in fig. 2.

The row of mirrors is normal to the south direction (the south direction defines $\phi_{\mathrm{sun}} = 0$, as indicated in fig. 2). When for instance the Sun is in the south, we can

([1]) Demonstraive movies are available in the website `www.isomorph.it/solutions/renewable-energies/solar-thermal/principle-of-functioning`

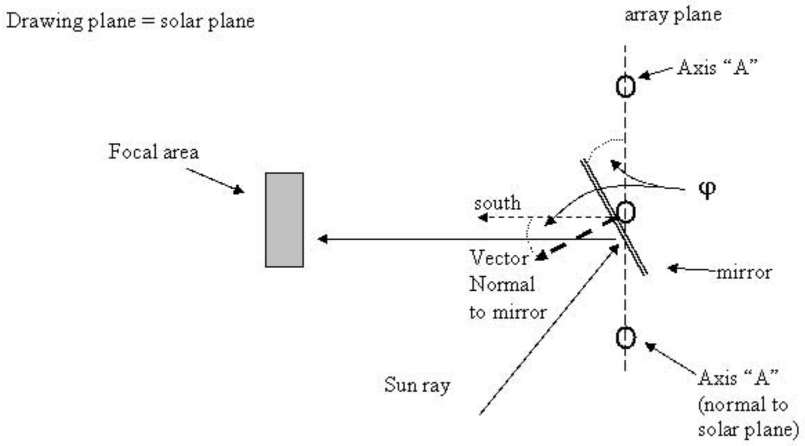

Fig. 2. – Top view of a horizontal slice of the array. Plane mirrors are mounted on axes "A" and rotate around them during the day. The angle of the mirror normal relative to south, which equals the angle between mirror and array, is denoted ϕ. The focal area has approximately the same size as the mirror.

adjust (in ϕ) each of the mirrors in such a way that all mirrors in a row reflect the Sun rays onto a common focal area, as indicated in fig. 2. When the Sun is in a different direction, the focal area remains fixed in space while the mirrors are rotated by $\Delta\phi_{\mathrm{mirror}} = 1/2\phi_{\mathrm{sun}}$. In this way, the reflected Sun light of this median row will point to the focal area during all day.

Several mirrors above (and below) the median row can be mounted on each axis, in order to increase the concentrating power of the system: this is sketched in fig. 3, which shows a vertical array of mirrors on one of the axes (normal to the incident Sun rays).

This mirror system would be very cheap, due to the simplicity of its construction. However, if we consider rotating the mirrors around their axes in order to follow the Sun during the day, as sketched in fig. 2, we observe that its optical properties are inadequate as discussed in the following.

We assume that each mirror is tilted up-down and left-right by the appropriate amount as to reflect the Sun rays onto the focal area when the Sun is in the south direction ($\phi_{\mathrm{sun}} = 0$). We shall call this "the ideal case". When the Sun is in a different direction,

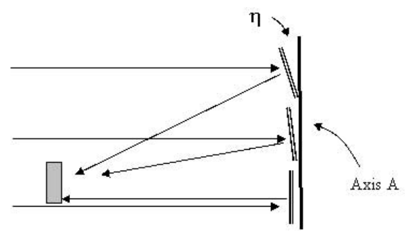

Fig. 3. – Side view of a vertical (normal to the Sun rays) slice of the mirror array. Most mirrors have an inclination η with respect to the axis A, so that when the mirrors are rotated in ϕ during the day the reflected rays are not normal to the vertical axis "A".

the focal area remains fixed in space while the mirrors are rotated by $\Delta\phi_{\text{mirror}} = 1/2\phi_{\text{sun}}$. As discussed before, for those mirror vectors which are normal to the axis to which they are mounted, the reflected Sun light will point to the focal area during all day. However, most mirrors would not be normal to their axes and tilted in the vertical direction as illustrated in fig. 3.

If now the mirrors are rotated according to $\Delta\phi_{\text{mirror}} = 1/2\phi_{\text{sun}}$ during the day, the mirrors with $\eta \neq 0$ will not reflect the light on the focal area precisely. We express the deviation of the reflected rays from the ideal case by considering the angle in space between the real reflected ray and the ideal ray (pointing precisely to the focal area). We label the projections of this angle as $\Delta\phi$ on the Sun plane and $\Delta\theta$ in the conjugate direction. The deviations $\Delta\phi$ and $\Delta\theta$ will of course be 0 for mirrors without inclination ($\eta = 0$), and will increase with η being larger for larger inclinations. In order to illustrate the problem we show in figs. 4 and 5 these deviations for a number of mirror inclinations. For simplicity only mirrors in the vertical slice at the centre of the array have been considered, for which $\phi_{\text{mirror}} = 0$ when the Sun is south, at $\phi_{\text{sun}} = 0$.

We see that for an inclination $\eta = 15°$ the deviations $\Delta\phi$ and $\Delta\theta$ will be as much as 4° and 6° respectively, for a Sun angle of $\phi_{\text{sun}} = 70°$ (2). If we therefore rotate all axes and mirrors by means of a single motor, according to $\Delta\phi_{\text{mirror}} = 1/2\phi_{\text{sun}}$, the reflections from the various mirrors would deviate from the focal area by less than about 6°. Since mirrors at small inclinations would have deviations smaller than 6° and since even the mirrors at large η will have smaller deviations then 6° during most of the day, this mirror system (which would be very easy to construct) would already have a significant efficiency and possibly be of practical use. In the following we shall illustrate how by simple means we can reduce these deviations to 1° or less and achieve a system of excellent light collection efficiency. Noticeably, this limit has great practical impact because large systems with mechanical tolerances much below 1° would be expensive to build.

2·1. *Making the mirror array approximately linear by means of linear operations.* – Figure 6 shows a simple way of correcting the $\Delta\phi$ deviations. Each mirror is mounted on an axis of its own and is rotated by means of a lever. The levers are all connected to a common axis of control, which is rotated by a motor. By appropriately choosing the length of each lever we can move the mirror axes at a speed different from the rotation speed of the axis of control. This allows reducing the deviation in $\Delta\phi$ to a fair approximation.

In order to reduce $\Delta\theta$ we use a system as is shown in fig. 7. Now, when the mirror is moving to left or right (in ϕ), it is also changing its inclination at the same time. This allows compensating some of the $\Delta\theta$ deviation.

We consider again the same mirror positions as in calculating the distributions of figs. 4 and 5. We also use the same values for the inclination η, but now the inclination of the mirror is achieved by a support system according to fig. 7. The length of the levers is optimised. As a result we get the $\Delta\phi$ and $\Delta\theta$ deviations as shown in figs. 8 and 9.

Now the $\Delta\phi$ deviation for a mirror with inclination $\eta = 15°$ is much less than 1°, to be compared to 4° as observed in fig. 4.

For $\eta = 15°$ the deviation in $\Delta\theta$ is less than 1° to be compared to $\simeq 6°$ in fig. 5.

(2) For angles larger than $\phi_{\text{sun}} = 70°$ the effective area of the array exposed to the Sun is less than 34% ($\cos(70°) = 0.34$). A coverage of $\pm 70°$ results in an exposure of $12\,\text{h} * 140°/180° = 9.3$ hours per day.

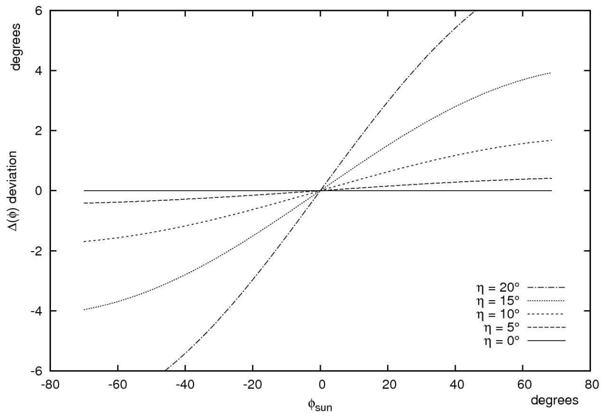

Fig. 4. – For a vertical slice of mirrors at the centre of the array, deviation of the reflected light ray from the ideal direction for different inclination angles η. The mirrors rotate around an axis normal to the Sun rays.

2·2. *Aberrations of light from non-central mirrors*. – In figs. 8 and 9 we have calculated the deviations for mirrors of a vertical slice at the centre of the array. The corresponding distribution for the uppermost and outmost mirror of the system shown in fig. 1 is shown in fig. 10. Compared to central mirrors, the focal quality is somewhat decreased but the deviations are still within $\sim 1°$.

3. – Measurement of the power transfer in a linear mirror with 20 mirror elements

A prototype of the linear mirror of size $4\,\mathrm{m} \cdot 2\,\mathrm{m}$, consisting of an array of 50 mirrors has been constructed. Due to financial constraints for the time being we have mounted

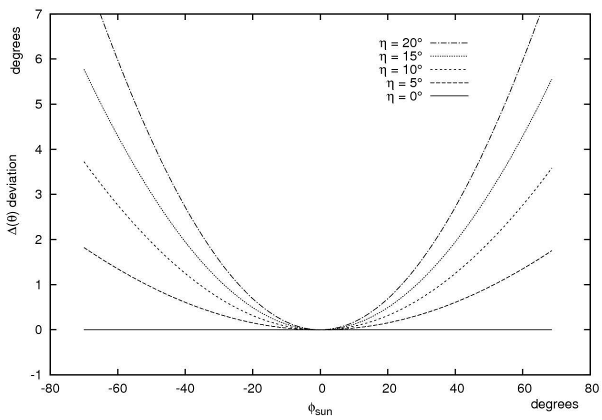

Fig. 5. – For a vertical slice of mirrors at the centre of the array, deviation of the reflected light ray from the ideal focal point for different inclination angles η. The mirrors rotate around an axis normal to the Sun rays.

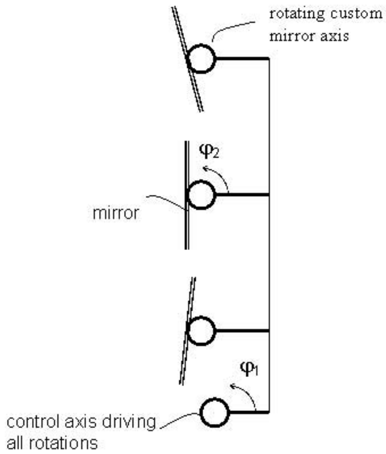

Fig. 6. – A common axis of control rotates by ϕ_1, causing a mirror to rotate by a different angle, ϕ_2.

only 20 of the 50 mirrors, as shown in fig. 11. The orientation of the mirror system towards the Sun was regulated by hand, using a gauge mirror. The oven of the system consists of a tin container of size $55\,\mathrm{cm} \cdot 55\,\mathrm{cm} \cdot 1\,\mathrm{cm}$. It was painted with a black colour as used for painting car motors. The container was filled with 4.3 litres of water (the container widened to a width of more than 1 cm when filled with water). The irradiated container is shown in fig. 11. The oven had no isolation at all.

The goal of the experiment is to determine the increase in water temperature as a function of time. The heat capacity of water is known ($4.180\,\mathrm{kJ/(kg{\cdot}K)}$), as well as the mass of the water (4.3 kg). Therefore the temperature increase per time gives a measure of the radiation energy absorbed by the water volume (the mass of the iron container is 8.0 kg, which is larger than the mass of the water, but the specific heat of iron is much less than that of water, so that the energy absorbed by the iron container can be ignored in this context).

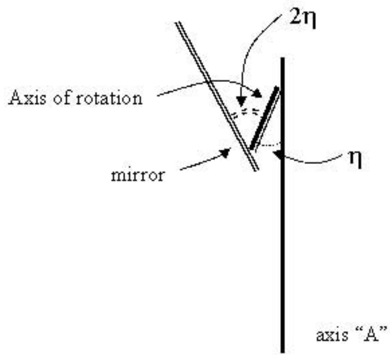

Fig. 7. – The axis of rotation of the mirror is not normal to the Sun rays anymore. It is inclined by η relative to "A", while the mirror is inclined by 2η with respect to its axis.

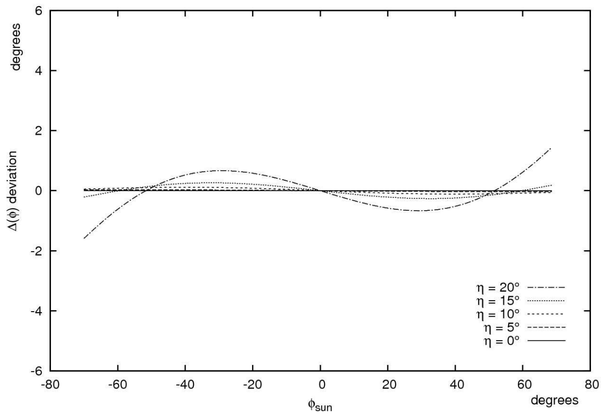

Fig. 8. – For a vertical slice of mirrors at the centre of the array, deviation $\Delta\phi$ of the reflected light ray for mirrors with corrected rotation. Note that the x and y scales are the same as in fig. 4.

3·1. *Description of the experiment.* – The measurement was performed on November 16th 2008, at noon time. A digital thermometer was used with high temperature resistant sensors. At time $t = 0$ the measurement started and the mirrors were turned onto the oven. Since there was only one person for operating the mirror system and for reading the thermometer, the start of the measurement at $t = 0$ and the activation of the mirrors were not perfectly coincident, for which reason the measurement at $t = 0$ will be reported in the following, but it will not be used for a quantitative evaluation. Figure 12 shows the temperature measured in the water volume with time. The temperature increase depends on two effects: first, there is the energy absorbed by the oven, causing an increase in water temperature. Second, heat will be lost to the environment. In order to estimate the loss of heat energy to the environment we have switched the linear mirror off (rotating

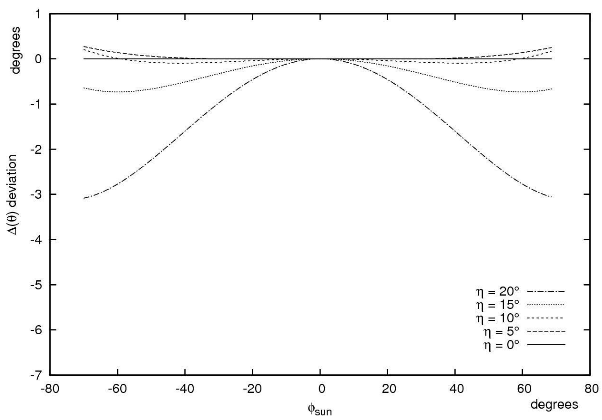

Fig. 9. – For a vertical slice of mirrors at the centre of the array, deviation $\Delta\theta$ of the reflected light ray for mirrors with corrected rotation.

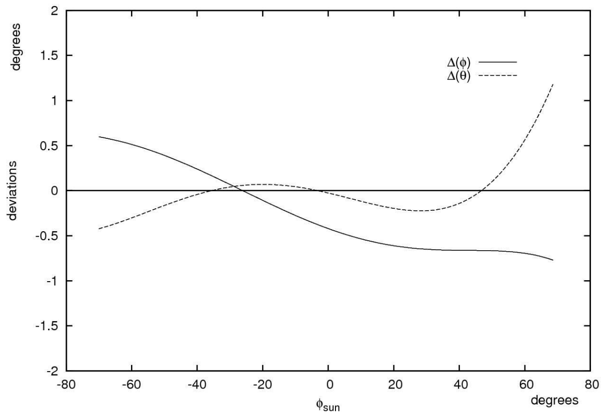

Fig. 10. – $\Delta\phi$ and $\Delta\theta$ deviations for the outmost and uppermost mirror on the corner of the mirror array of fig. 1.

its mirrors sidewards), as shown in fig. 12: at the time intervals (b,c) and (d,e) the oven was not heated. For the time interval (b,c) (and a temperature of 53 °C) a decrease in temperature cannot be noted. For the time interval (d,e) (and a temperature of 75 °C) a slight decrease in temperature can be observed, indicating a relatively larger loss of heat energy at this higher oven temperature.

As mentioned above, the measurement suffers from a systematic uncertainty at around $t = 0$, so we use for the analyses the time from point (a) and later. In the time interval between (a,b) (from $t = 1.35$ min to $t = 4.26$ min) the temperature increased from 36.8 °C to 52.0 °C. This means that the heat energy of the oven increased at a rate of 1.6 kW. For the time interval (e,f) we find instead an increase of heat energy at a rate of 1.3 kW, due to the higher temperatures and the correspondingly higher heat loss. The mean temperature in the interval (a,b) is 44.4 °C and in the interval (e,f) it was 69.6 °C. The ambient temperature was about 15 °C. The temperature difference between oven and environment was therefore larger for the measurement (e,f) by a factor of 2.4 compared to the measurement (b,c). Assuming that the heat loss to the environment increased

Fig. 11. – Left: mirror array of 20 elements with oven. Right: view of the oven with the water boiling (taken from behind the mirrors). The white paper fixed below the oven serves for reading the signal from the gauge mirror needed for regulating the system.

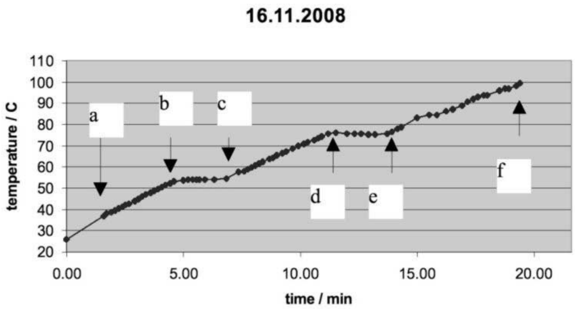

Fig. 12. – Temperature of the water (in degree Celsius) as function of time.

with ΔT at least linearly, we conclude that in the interval (a,b) the heat loss was at least 0.2 kW (while it was 0.5 kW at (e,f)). That means that the oven absorbed between 1.6 kW and 1.8 kW of heat power during the experiment from the mirrors.

Since the 20 mirrors (of $40\,\mathrm{cm} \cdot 40\,\mathrm{cm}$ each) have a total area exposed to the Sun of $3.2\,\mathrm{m}^2$, a total power of 1.8 kW corresponds to a power of 0.56 kW for each m^2 of mirror surface. Given that the experiment was performed in mid November, this value is at least satisfying, since it corresponds about to the primary radiation density at the Earth surface at this time of the year.

About one hour after having reached 100 °C the water had evaporated and the temperature in the oven increased continuously up to 200 °C.

These numbers indicate that the completed device with 50 mirrors should be able to make 1 litre of water boil within about 1 minute and it should be able to reach temperatures well above of 300 °C—sufficient for operating a heat engine.

4. – Conclusions

We have presented in this paper a very simple system of mirrors, which are operated by only two motors, and which are able to project Sun rays onto a common focal area with a precision of about 1° during most of the day [6]. Such a system should be very easy to build and should therefore be very cheap. We estimate that a cost of about 200 euro/m^2 should be achievable. This focusing system has been patented (patent no. PCT/EP2008/002661). A small size prototype has been tested providing a power of 0.56 kW per m^2 of mirror surface in mid November.

In the focal area one can heat air, water, vapour or similar media, and depending on the specifications of the system temperatures up to several hundred degrees Celsius should be easily obtained. This allows providing high temperature steam for electricity production and heat of easy practical use. Due to the high temperatures to be achieved, the heat would not only be well suited for heating buildings directly, but would also be relatively easy to be stored or to be used in industrial processes like air conditioning or bio-ethanol production.

Finally, we note that we presented only a very first step into a new technology, which presumably leaves much room for further future improvements. Due to its low cost, its versatility and the possibility to store the produced energy, the system would allow significant savings of oil and coal. The system should be of major interest in regions close to the equator, but it should be competitive also in more northern (or southern) Countries like Germany or Canada.

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