DOUBLING THE PERFORMANCE-COST RATIO OF PV BY USING CHEAP MIRRORS – A SECONDARY SCHOOL PROJECT

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ABSTRACT: Reduction of cost is a major issue in the photovoltaics field. We have addressed this issue in a secondary-school science project by considering the use of cheap mirrors in combination with solar panels, for application in developing countries. We have confirmed that it is possible to increase the performance-cost ratio of solar cells by using mirrors. With geometric analyses of several configurations involving a solar panel and mirrors of different size, in combination with measurements, we have shown that a performance enhancement can be reached of 126%, with respect to a horizontally placed solar panel. This performance enhancement can be reached at only 30% higher cost using a solar cell in combination with an elongated mirror made of commercially available bathroom tiles. However, using an Al foil elongated mirror a performance enhancement can be reached of 120% at 10% higher cost. Therefore, the use of an Al foil is more cost effective than the use of bathroom tiles.
Keywords: Energy performance, Mirror, Cost, Developing countries

1 INTRODUCTION

Secondary school students belonging to the top 5% of their population are encouraged to enlist in the Junior College Utrecht (JCU) [1], where they are offered a high level education in natural sciences. Some 25 schools in the Utrecht region participate in this exchange programme. Per school 1 to 2 excellent students annually are allowed to take part in the 2-year programme. They attend various natural science courses, and as part of the curriculum of the second year, a science project has to be developed and worked out during a period of 5 months (200 hours total). Other courses, such as the ones on languages (Dutch, English), history, geography, are followed at the students' school of origin. JCU also is started as a laboratory to experiment with and develop new educational methods and tools in the field of natural science. To this end, a strong collaboration is maintained between the 25 regional secondary schools, and Utrecht University.

As science project, we (HdB, SvH, BK) have developed a project in the field of concentrated photovoltaics (PV) as we were motivated to address the issue of the current high costs of PV modules. Several approaches exist to lower the costs, see for example the recently published Strategic Research Agenda of the European Photovoltaic Technology Platform [2]. One of the possible solutions is the use of concentration by means of lenses or mirrors [3]. In this way, more light is directed toward the solar cells, which will generate more power compared to unconcentrated sunlight. Concentration factors of 500-1000 can be reached using cheap plastic lenses in combination with expensive III-V triple junction solar cells [4].

Our approach is to focus on the use of mirrors that are made of simple, cheap, and readily available materials. Application of mirrors enhances the power output of PV modules, and concentration factors between 1 and 5 can be reached [5]. PV performance is enhanced while keeping additional costs of mirrors low. We thus aim at increasing the performance-cost ratio, in kWh/€, and our research question therefore is as follows: *"is it possible to increase the performance-cost ratio of solar cells by using mirrors"*. The mirrors should be as cheap as possible, and should be manufactured or found locally, as the possible increase is of special interest for applications in sunny regions of the developing world. We have tackled this question by means of experimental work in order to determine the increase in power from a small amorphous silicon solar panel using different panel-mirror configurations. Also, to determine the maximum theoretical gain we have performed geometrical calculations for several configurations and several mirror materials, each with a different reflectance. We will present several configurations of which the performance-cost ratio can be nearly doubled compared to a solar panel positioned horizontally.

2 THEORETICAL CONSIDERATIONS

2.1 Geometry

In the following we calculate the amount of incident irradiation on a solar cell for several configurations employing a mirror, and we compare that value to the one for a solar cell that is placed horizontally (base case, without mirror). For the base case the amount of incident irradiation I_{cel} is easily calculated to be

$$I_{cel} = I_0 \sin\alpha ,$$

where I_0 is the angle dependent incident irradiation, and α the incident angle, which varies between 0 and 180°.

2.1.1 Static 90°-configuration

We first consider the configuration where a solar cell or panel is placed at an angle of −45° with respect to the normal, which points upwards vertically; the mirror is placed at an angle of +45°. The solar cell and mirror are thus perpendicular, hence the term 90°-configuration. In addition, the solar cell and mirror are equal in size. We can distinguish four cases, and for each case the amount of incident irradiation I_{cel} is calculated with

$$I_{cel} = I_d + I_m ,$$

where I_d is the direct contribution and I_m the contribution from the mirror. In general, reflection from the mirror can be characterized with a reflection coefficient *r*. The four cases are shown in Fig. 1.

For these four cases, we can derive the following equations, assuming $r = 1$:

(1) $0^\circ \le \alpha \le 45^\circ$:

$$I_{cel} = 0 + 0 = 0$$

(2) $45^\circ \le \alpha \le 90^\circ$:

$$I_{cel} = I_0 \sin\left(\alpha - \frac{\pi}{4}\right) + I_0 r \sin\left(\alpha - \frac{\pi}{4}\right) = 2I_0 \sin\left(\alpha - \frac{\pi}{4}\right)$$

(3) $90^\circ \le \alpha \le 135^\circ$:

$$I_{cel} = I_0 \sin\left(\alpha - \frac{\pi}{4}\right) + I_0 r \sin\left(\frac{3\pi}{4} - \alpha\right) = \sqrt{2} I_0 \sin\alpha$$

(4) $135^\circ \le \alpha \le 180^\circ$:

$$I_{cel} = I_0 \cos\left(\alpha - \frac{3\pi}{4}\right)\left(1 - \tan\left(\alpha - \frac{3\pi}{4}\right)\right) + 0 = \sqrt{2} I_0 \sin\alpha$$

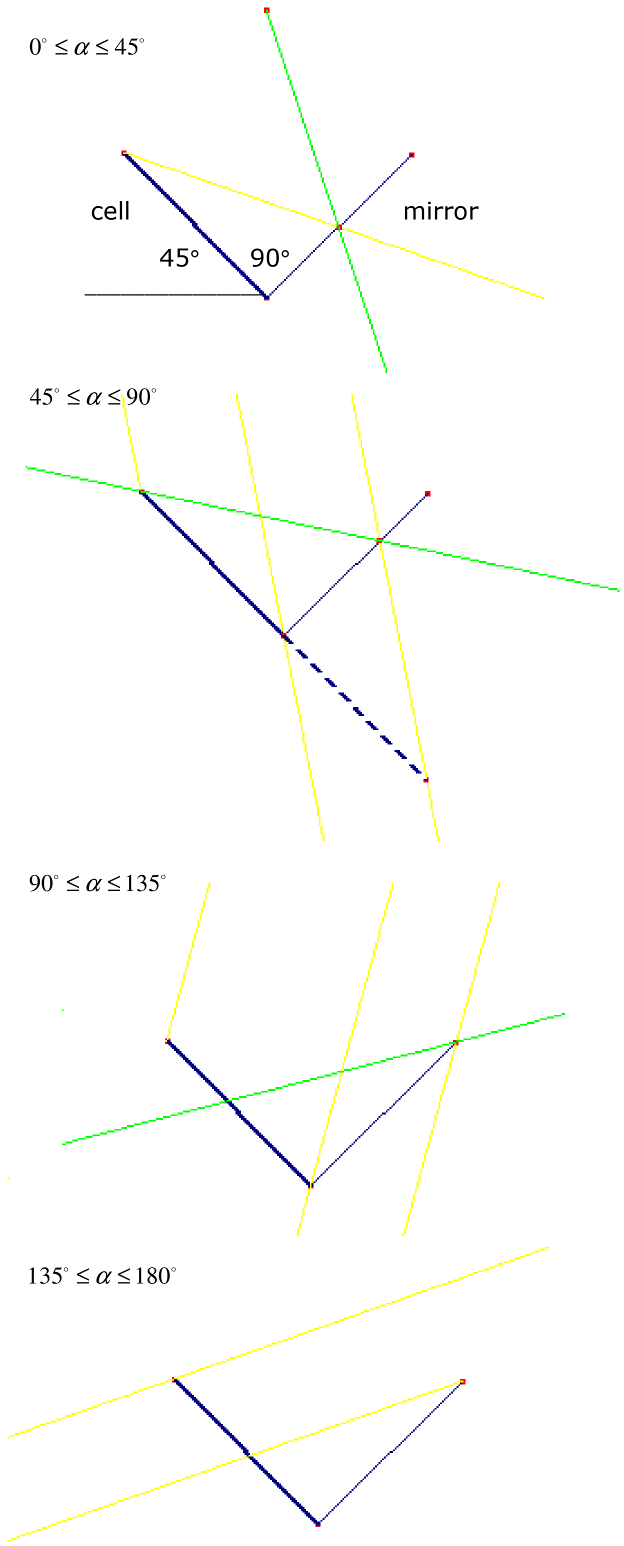

Figure 1: Four situations, depending on the incident angle α: $0^\circ \le \alpha \le 45^\circ$, $45^\circ \le \alpha \le 90^\circ$, $90^\circ \le \alpha \le 135^\circ$, and $135^\circ \le \alpha \le 180^\circ$. Incident light is depicted in yellow, reflected light in green

The resulting relative amount of irradiation incident on the solar cell I_{cel}/I_0 is shown in Fig. 2. A comparison of this 90°-configuration with the horizontal base case is shown in Fig. 3. For angles larger than 75° a relative enhancement is clear. For angles between 90° and 180° the enhancement is $\sqrt{2}$, which directly follows from comparing the equations above.

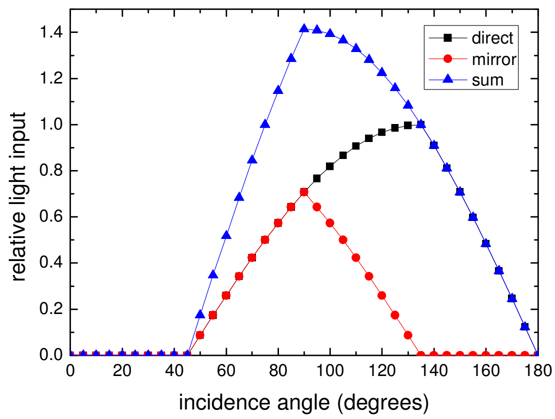

Figure 2: Relative amount of irradiation incident on the solar cell, also showing the contributions from direct incidence and the mirror

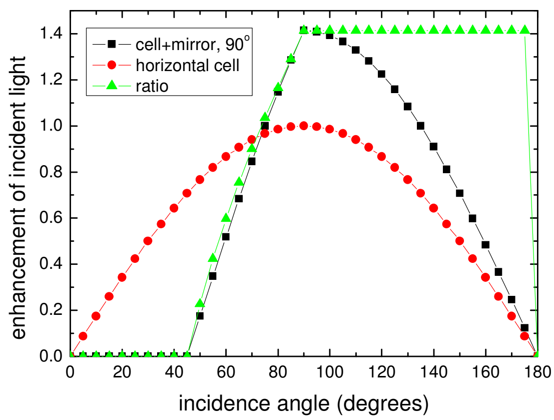

Figure 3: Comparison of 90°-configuration with horizontal one

2.1.2 Dynamic 90°-configuration

This configuration is identical to the static one, but the configuration is rotated such that it follows the sun, using some sort of tracking device: compared to the static configuration the angle of incidence always is 90°, so that

$$I_{cel} = I_0 \sin\left(\frac{\pi}{2} - \frac{\pi}{4}\right) + I_0 r \sin\left(\frac{\pi}{2} - \frac{\pi}{4}\right) = 2 I_0 \sin\left(\frac{\pi}{4}\right) = \sqrt{2} I_0 .$$

2.1.3 Dynamic configuration with longer mirror

In this configuration the mirror is elongated with respect to the solar cell, as shown in Fig. 4 (by a factor 2.5). The solar cell and mirror are thus no longer perpendicular to each other. We find:

$$I_{cel} = I_0 \sin\left(\frac{\pi}{2} - \frac{\pi}{4}\right) + I_0 r = I_0\left(\sin\left(\frac{\pi}{4}\right) + 1\right) = \left(1 + \sqrt{2}\right) I_0 .$$

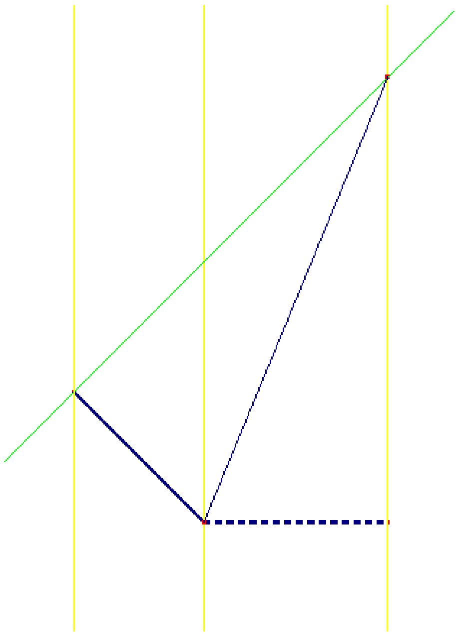

Figure 4: Configuration with elongated mirror (2.5 times compared to the configuration of Fig. 1). The dotted line represents the projection of the mirror on the horizontal surface

2.2 Daily variation of irradiance

The variation of irradiance during the day is determined using the simulation programme HOMER [6], using the equator as geographical locations. The values are found on an hourly basis. As we use the equator, we can safely assume that the length of the day is 12 hours on average, with sunrise at 6 AM and sunset at 6 PM. We thus can convert the hourly values to values as a function of incident angle; the result is shown in Fig. 5.

The amount of irradiance calculated by HOMER is per unit of area. As the incident angle varies during the day, the area that the solar beam spreads out over varies as well. We need to find the ratio of beam diameter and horizontal surface area, and correct the data in Fig. 5 for that. The ratio of beam area and surface area equals $\sin\alpha$, and the corrected data are thus found by dividing the original data by $\sin\alpha$, see Fig. 5. From this we infer that the relative irradiance does not vary much during the course of the day, and we therefore assume that I_0 is independent of α.

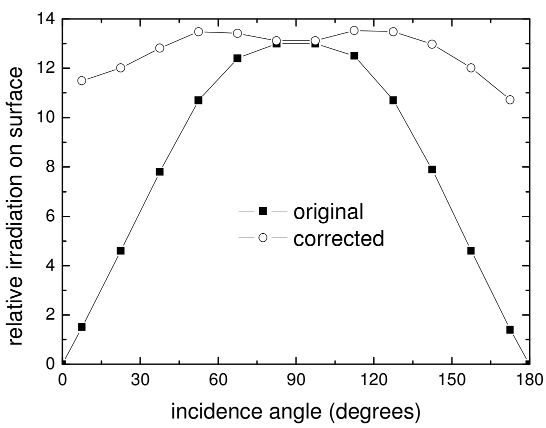

Figure 5: Variation of irradiance during the day. The original data are determined from within HOMER; the corrected data refer to a correction related to beam projection

3 MEASUREMENT SET-UP

A photograph of the measurement set-up is shown in Fig. 6. It reflects the static 90°-configuration with incident angle of 90°, and also the dynamic 90°-configuration, both with equal size of solar panel and mirror. For the horizontal base case, the mirror was removed and the solar panel was rotated by 45°. The solar panel was 30×30 cm^2 in size, with performance parameters measured at 1000 W/m^2 incident irradiation: short-circuit current I_{sc}=435 mA, open-circuit voltage V_{oc}=20.8 V fill factor FF=0.561, and maximum power P_{peak}=5 W. We used three types of mirrors: 1) bathroom mirror tiles (4 pieces of 15×15 cm^2); 2) aluminium foil; 3) inside of a chips bag. The latter two mirror materials are fixed on a piece of carton board. As a control, also measurements were performed without mirrors, for the same 90°-configuration.

As light source we used a strong 850 W construction lamp, at about 2 meter above the solar panel [7]. The light intensity was measured using a Lux meter. The intensity was converted from Lux into W/m^2. For all measurement situations we varied the lamp-solar panel distance such that the intensity at the solar panel always amounted to 36.5 W/m^2.

The current-voltage characteristic is measured using a variable resistor (0-1 MΩ), and two multi-meters, one for the current, and one for the voltage, see Fig. 7 [7]. As a small voltage remains over the current meter, the measurement voltage is somewhat smaller than the actual voltage over the cell. The maximum power is found from multiplying current and voltage.

Figure 6: Photograph of the measurement set-up, showing HdB and BK (photograph taken by SvH)

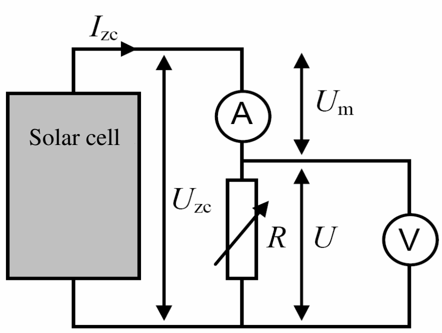

Figure 7: Measurement circuit [7]

4 RESULTS AND DISCUSSION

4.1 Measurements

The current-voltage characteristics for all configurations are shown in Fig. 8. The performance parameters short-circuit current I_{sc}, open-circuit voltage V_{oc}, fill factor FF, and maximum power P_{peak}) are summarized in Table. I. It is clear that the use of mirrors is beneficial: the output is increased by 20-23% with respect to the flat configuration. The increase in short-circuit unfortunately is counterbalanced by the decrease in fill-factor, as a result of a larger resistive loss due to the larger current. Note also that the fill factor is larger than the one specified at 1000 W/m^2, also due to resistance effects, see also Reich *et al.* [8].

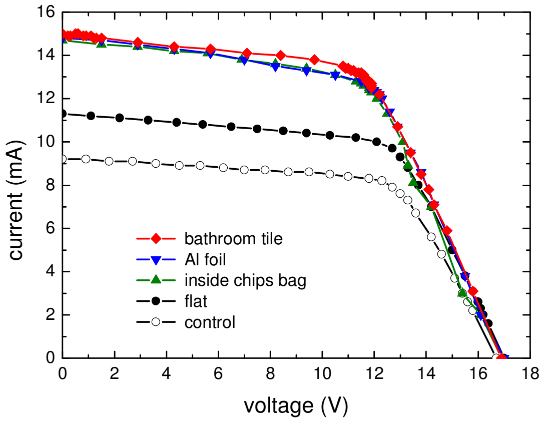

Figure 8: Current-voltage characteristics for all configurations

Table I: Measured performance parameters short-circuit current I_{sc}, open-circuit voltage V_{oc}, fill factor FF, and maximum power P_{peak} for all configurations. P_{norm} is the power normalized to the flat configuration

Configuration	I_{sc} (mA)	V_{oc} (V)	FF	P_{peak} (mW)	P_{norm}
Flat	11.3	17.0	0.641	123.2	1.000
Control	9.2	16.7	0.656	100.9	0.819
Bathroom tiles	15.0	16.9	0.599	152.0	1.234
Al foil	14.8	17.0	0.592	148.8	1.208
Inside chips bag	14.7	16.9	0.594	147.5	1.197

4.2 Adjustment of geometrical calculations

The measurement set-up reflects the static 90°-configuration with incident angle of 90°, and also the dynamic 90°-configuration. From Fig. 3 we infer that the increase in power output would be $\sqrt{2}$. The data in Table I show a smaller increase. This is due to the fact that we assumed a reflection coefficient of the mirror $r = 1$. We can find the reflection coefficients for the used materials, using

$$I_{cel} = I_0 \sin\left(\frac{\pi}{2} - \frac{\pi}{4}\right) + I_0 r \sin\left(\frac{\pi}{2} - \frac{\pi}{4}\right) = \frac{(1+r)\sqrt{2}}{2} I_0 ,$$

and

$$P_{norm} = \frac{(1+r)\sqrt{2}}{2} .$$

For the bath room tiles we find the largest reflection coefficient of $r_b = 0.744$; for the Al foil $r_b = 0.744$, and $r_c = 0.693$ for the chips bag. With these data we can recalculate the angle dependent enhancement for the static 90°-configuration for the three materials used, see Fig. 9.

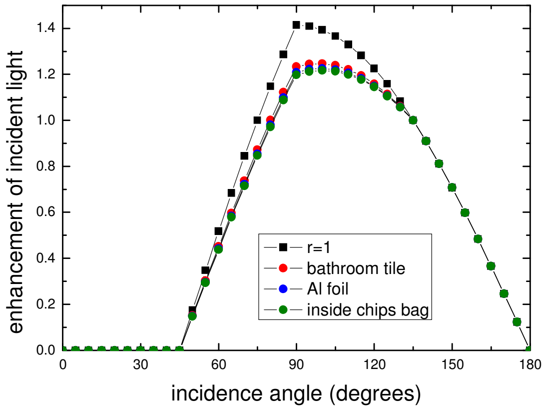

Figure 9: Relative amount of irradiation incident on the solar cell, recalculated using the actual reflection coefficients of the materials used

At 90° incidence angle, this is equal to the measurement results. For the dynamic configuration with longer mirror, the enhancement is

$$I_{cel} = I_0 \sin\left(\frac{\pi}{2} - \frac{\pi}{4}\right) + I_0 r = \left(r + \frac{1}{2}\sqrt{2}\right) I_0 .$$

Using the reflection coefficients we find an enhancement of 1.452, 1.416, and 1.400, for the bathroom tiles, the Al foil and the inside chips bag, respectively.

4.3 Combination of results

Combining the results shown in Fig. 9 with the corrected angle-dependent irradiation data of Fig. 5 yields performance enhancements factors as shown in Table II. Clearly, the use of a mirror in a static configuration lowers the performance by 7-8%, while a dynamic configuration including a mirror may lead to performance enhancements of 87-126%! Just using tracking enhances performance by 54%.

Table II: Relative enhancement for several configurations. Note that short and long denotes the use of short or long mirrors. The three numbers for the mirror configurations refer to the three materials used: bathroom tiles, Al foil, and the inside chips bag

	Enhancement
Static solar cell	1 (definition)
Dynamic solar cell	1.54
Static 90°-configuration (short)	0.929 – 0.918 – 0.914
Dynamic 90°-configuration (short)	1.924 – 1.884 – 1.867
Dynamic 90°-configuration (long)	2.264 – 2.208 – 2.184

4.4 Performance-cost ratio

To determine the cost of the system we assumed a module price of 4 €/Wp, and calculated the price per m^2 to be 222 €/m^2. The mirror prices should be much lower. We have used 20 €/m^2 for the bathroom tiles, which is based on studying local construction shop prices. Likewise, from supermarket investigations, the Al foil price is estimated at 0.11 €/m^2. We could not find data for chips bags, but consider the price to be equal or less than the Al foil price. Further, the price of the construction is estimated at 5-10 €/m^2, for the static configurations. For the dynamic configurations the price is doubled. Thus, for instance, the price of a short static 90°-configuration with bathroom tile mirror would be 250 €/m^2 (using 8 €/m^2 for the construction).

The performance-cost ratio can now be calculated; results are shown in Table III. The normalized performance for dynamic configurations is enhanced, but if a mirror is expensive the performance-cost ratio may not be larger than unity. Both bathroom tiles and Al foil are cheaper than solar cells in terms of €/m^2, and thus are the performance-cost ratio larger than unity. Although the performance enhancement by the Al foil is lower than that of the bathroom tile due to the lower reflection coefficient, the performance-cost ratio for the Al foil is the largest, which is due to the much lower price per m^2. Using a long mirror leads to larger performance-cost ratios with respect to a small mirror, while a long mirror made of Al-foil doubles the performance-cost ratio. To phrase this differently, it is possible to get 120% more power out of the solar panel at only 10% extra cost.

If only badly reflective materials are available, it is still useful to construct a mirror using those materials. E.g., for a material with reflection coefficient $r_c = 0.5$, the performance enhancement using an elongated mirror is 88%, while the cost increase is only 10%, assuming the reflective material to have lower cost than the Al foil. This still yields an enhancement of the performance/cost ratio of 1.7.

Table III: Normalized performance-cost ratio enhancement for several configurations, for bathroom tiles and Al foil mirrors

Enhancement	cost (€/m^2)	performance normalized	performance/cost normalized
Static solar cell	222	1	1
Bathroom tile			
Static	250	0.920	0.825
Dynamic	260	1.924	1.643
Dynamic long	290	2.264	1.733
Al foil			
Static	230	0.918	0.886
Dynamic	240	1.884	1.743
Dynamic long	245	2.208	2.001

5 CONCLUSIONS

We have shown that it is *possible to increase the performance-cost ratio of solar cells by using mirrors*, and thus have answered our research question affirmatively. The mirrors should be as cheap as possible, and should be manufactured or found locally, as the possible increase is of special interest for applications in sunny regions of the developing world. With geometric analysis, and measurements, we have shown that a performance enhancement can be reached of 126% at 30% higher cost using a solar cell in combination with an elongated mirror made of commercially available bathroom tiles. However, using an Al foil elongated mirror a performance enhancement can be reached of 120% at 10% higher cost. Therefore, the use of an Al foil is more cost effective than the use of bathroom tiles. Moreover, Al foil probably is readily available also in developing countries.

6 SUSTAINABLE DESIGN AWARD

This project was awarded the Sustainable Design Award 2007 from Twente University, the Netherlands. The jury of this annual award for secondary school science projects has praised this project for its high-tech content with a low-cost approach. A photograph of the award ceremony (April 5, 2007) is shown in Fig. 10.

Figure 10: The Sustainable Design Award is handed over to the three secondary school students

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