The linear mirror –
a cheap and simple solar concentrating system

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The linear mirror unites the advantages of simple conventional solar thermal systems with the advantages of more advanced concentrating solar systems. It is as cheap and as simple to operate as a conventional solar collector, and like a parabolic dish or trough it can reach high temperatures, also in winter, and it can deactivate itself if its energy is not needed.
At present the linear mirror is used for heating water up to 100 ºC, in order to heat buildings or provide hot water for restaurants, hotels or industrial applications at this temperature. In the future the linear mirror can be integrated with almost all energy consuming applications and it will reach much higher temperatures.

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Introduction

From a physics point of view, collecting solar energy should be easy. And therefore it should be cheap. All you need is a reflecting surface, which you direct towards the sun so that it reflects the sun light onto the spot where you need it.
The reflecting surface should be cheap: even a high tech aluminium mirrors costs not more than 30 € per m^2. With this surface of 1 m^2 you can collect almost 1 kW of solar energy, for typically 1.500 hours per ear – depending on the climate -, for a total of 1.500 kWh of energy per year, which is an equivalent of about 100 litres of Oil. So the reflecting surface costs much less than the energy, which it provides in one single year. Also directing the surface towards the sun should be cheap: you need a microcontroller and a very small electrical motor. The microcontroller costs 1 € and the motor a few.
There is an important physics difference between a solar system and for instance a wind turbine or a water turbine. A turbine is providing energy, ΔE, by means of large moving forces, F, according to the formula $\Delta E = F \cdot \Delta x$, known from school
On the mirrors of a concentrating solar system instead there is almost no force. The particles of the sun light, called photons, do create a certain pressure force on the mirror, but this pressure is so tiny, that one can ignore it from an engineering point of view. Why are then existing concentrating solar systems so expensive and complex?

State of the art

To build a small solar cooker from a reflecting parabolic dish is easy and should not be too expensive. The reflector alone for a device of 1 m^2 should cost of the order to 100 € at maximum and have a weight corresponding to a mass of one or few kg. Building larger devices is much more difficult, since the parabolic shape must be maintained over a large surface, and as a consequence, the mechanical structure gets heavy. This heavy structure must now be mounted on and moved around two mechanical axes at a high precision. The overall device also has to withstand the wind forces without significant bending. The wind force on a parabolic dish is about as large as the wind force on a wind turbine of the same size!
The mechanical structure of a parabolic trough system is simpler, since the parabolic trough rotates around only one axis, not two. But this advantage comes with an unavoidable disadvantage, which is the heat exchanger. The heat exchanger in a parabolic trough system must necessarily have the shape of a long tube, made of high tech materials and using high tech procedures, and that cannot be cheap.
Very similar to the parabolic trough type system are systems using the Fresnel principle.
The most simple and therefore most attractive system seems to be the solar tower or heliostat system. Many mirrors placed around a tower reflect their light on top of the tower, where a heat exchanger is mounted. This system is very attractive, since it can be extended to a large size, a very large number of mirrors can illuminate only one heat exchanger. For instance, the construction of a solar tower system with a reflecting surface of 1000 m^2 illuminating a common heat exchanger is quite straightforward, while the construction of one single parabolic dish of 1000 m^2 would be very difficult. Unfortunately, all known heliostat systems use two motors for each of the many mirrors in order to make the mirrors follow the sun. This makes the system expensive.
All of those technical problems can be solved of course. As a result, we see the first commercial solar parks based on concentrating solar techniques all over the world, and they are working well. Their wide spread use is limited only by two facts: due to their price,

they make sense only in very sunny climates, like in the south of Spain or in Africa. And due to their complexity, they require dedicated parks run by expert personal.
If one could remove only one of the limitations of present technology, the economic use of concentrating solar power systems also in northern climates and for the mass market might become feasible. This would be a precondition for substituting fossil and nuclear power sources.

The linear mirror principle

It is very difficult to imagine a parabolic dish or a parabolic (or Fresnel) trough system without the disadvantages of such a system. For the solar tower principle instead one may ask, whether it is really necessary to operate each of the many mirrors by two motors - how many motors are really needed in order to operate N mirrors?
In order to get an answer to this question one needs to consider, that a system of many mirrors is not a mechanical machine, in as far as it does not transfer energy by means of moving under forces. One can rather describe it as a calculator, or an information processing system: it has an input, consisting of the actual time and its geometrical position, from that the sun position is calculated, and as output result the positions of the mirrors. The research company Isomorph srl has over the last years developed a physics theory of information, and as a matter of fact, the linear mirror is an application of this theory
The physics of information is an attempt to introduce physics concepts and physics variables into the theory of information. The current theory of information, as founded by Shannon and the algorithmic information theory as developed by Kolmogorov and Chaitin are formal theories, without physics variables. But instead information processing systems, like computers or brains are part of the physical world, and therefore their operation should be described by physics laws. A more detailed discussion of the theory of information can be found on the web pages of the Isomorph scientific journal (for more details refer to http://www.isomorph.it/letters/articles/on-the-mathematical-structure-of-messages-and-message-processing-systems).
Here we mention only briefly one result, relevant for the construction of the linear mirror: according to the physics of information, each calculation in the physics world (where messages are always finite) can be driven by a linear function. As a consequence, each of the movements of the mirrors of a system of mirrors can be expressed in terms of a linear function. And all of these functions can again be derived from one common linear function. That means that from a theoretical point of view it must be possible to operate a system of N mirrors with only one motor.
An example for illustration are the astronomic clocks. An astronomic clock has several hands, each points to the position of a planet or the sun or the moon at any given time. Though this has never done in practice, it seems reasonable to assume that one can mechanically connect the hand showing the sun position to a mirror, such that the mirror will follow the movement of the sun. This can then be done also with N mirrors, each one with its astronomic clock attached. But all of these clocks are driven by the same simple clock, performing always the same linear movement. So we can substitute the multitude of clocks by one single clock. The linear motion performed by this clock will make all the N mirrors follow the sun.
An alternative way of understanding this is to consider, that given the geographic position of the N mirrors, the time shown by a clock is containing all of the information needed to determine the actual sun position, and this information is identical for all N mirrors.

It follows, that an array of N mirrors concentrating sun light onto a common heat exchanger can in principle be driven by only one motor. Of course, any number of motors larger than one is also possible, for instance 2N motors - 2 motors for each mirror -, as in a heliostat system. It becomes then possible to choose an optimal number of motors. For instance using one motor only may require a complicated gear, like in an astronomic clock, so that using two motors might be more convenient, one for the azimuth, one for the zenith movement of the sun.

The linear mirror technology

To focus sun light during the day always onto the same spot is trivial, if the light ray arriving from the sun, the reflected light and the seeming sun path (the seeming movement of the sun around the earth) are in one plane. In this case the reflecting mirror needs to rotate around an axis normal to this plane at a velocity, which is half of the sun's angular velocity. This is shown in Figure 1. (a demonstrative movie can be found on www.isomorph.it/solutions/renewable-energies/solar-thermal). We may assume that in figure 1 the heat exchanger (shown in grey) is in the south direction with respect to the mirror (blue). Then the left picture shows the sun in the morning and the right picture shows a situation in the afternoon.

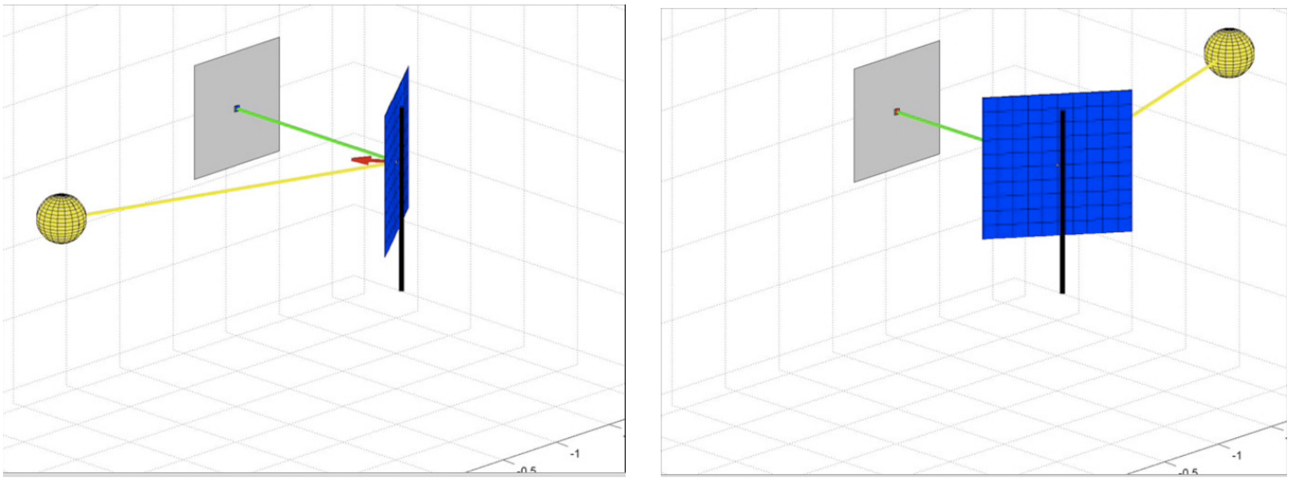

Figure 1: mirror rotating around an axis normal to the plane of the seeming sun movement. Sun movement, sun ray (yellow) and reflected ray (green) are in the same plane. The reflection occurs in the centre of the mirror.

The problem then is, that in a two-dimensional array of reflecting mirrors most of the mirrors have to reflect the light out of the plane of the sun rotation – upwards or downwards -, in order to send the light onto the common heat exchanger. If we simply incline the mirror correspondingly (but have it still rotate around the same axis normal to the sun plane), we get the situation shown in figure 2. The light is not anymore reflected onto one and the same spot during the day. (So this system cannot concentrate the sun light.) But rather the light reflection performs an up- und down movement on the heat exchanger.

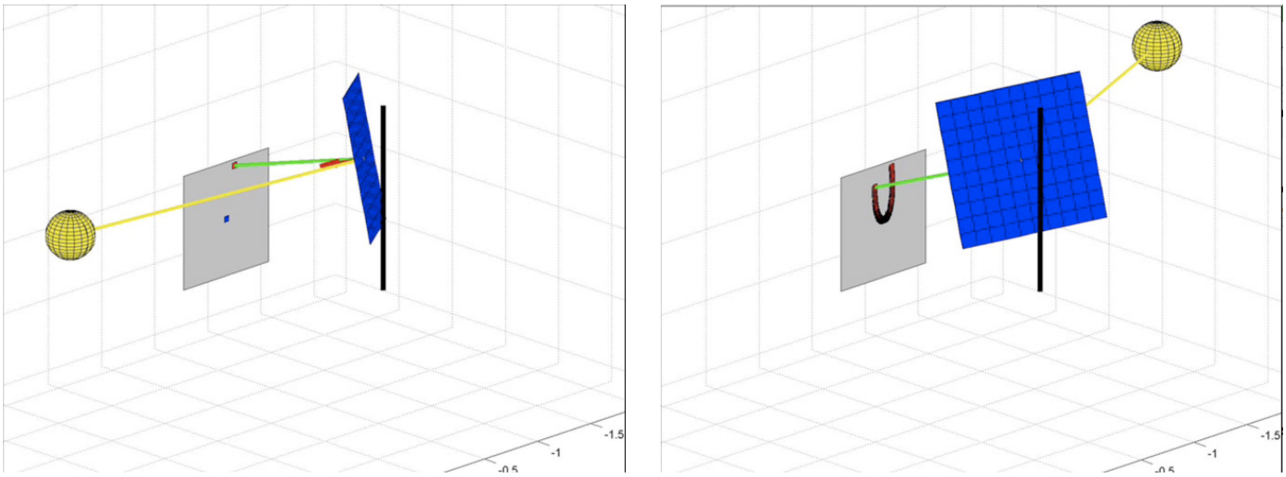

Figure 2: reflection of sun rays from a mirror which rotates around an axis normal to the sun plane, being inclined with respect to this axis.

One can in large part compensate this up- and down movement of the light reflection, if one makes also the mirror move up and down while rotating around its axis.
An example for this is a door, which is not mounted correctly on its hinges. Assume the hinges to be distorted in such a way, that the axis of rotation of the door is not vertical. Then the door will be slightly lifted or lowered when opening it, depending on how the axis of rotation deviates from the vertical.
The same principle can help us to make the mirror move upwards and downwards during its rotation, as shown in figure 3. The mirror is mounted on an axis, which is “distorted”, deviating from the vertical.

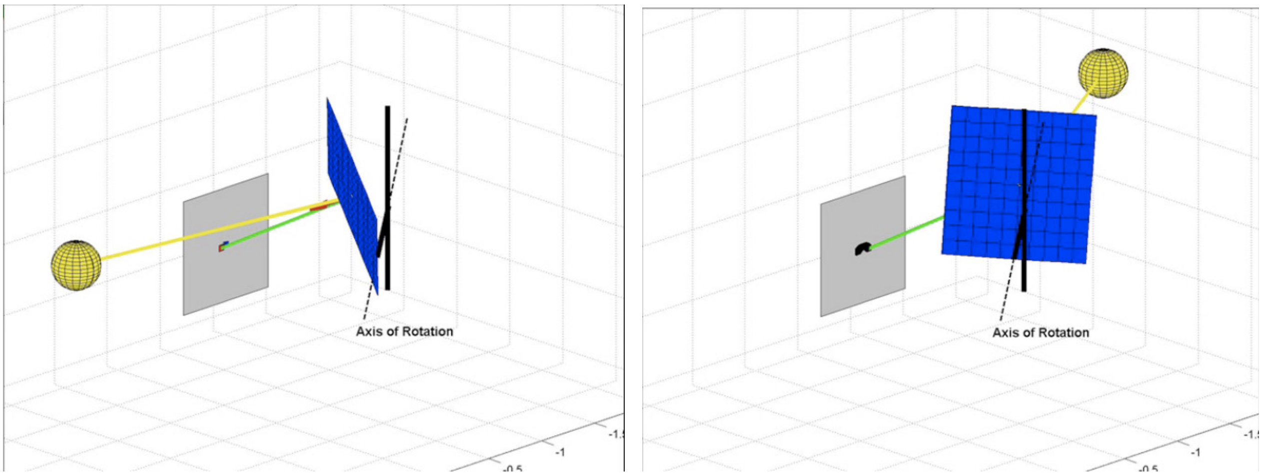

Figure 3: a mirror mounted onto an axis in such a way, that during the left-right rotation it also changes its inclination.

Adjusting also the velocity of the rotation, we reduce significantly the deviation of the light reflection from the centre of the heat exchanger, as shown in figure 3.
While this method is not mathematically perfect (one does not obtain a reflection on always the same point) it is simple and therefore cheap, and it is precise enough for all practical purposes.

We can now create an array of mirrors, where the mirrors are mounted on a very simple mechanical structure, shown in figure 4, where each mirror sits on an individual axis, chosen according to the principle shown before in figure 3.

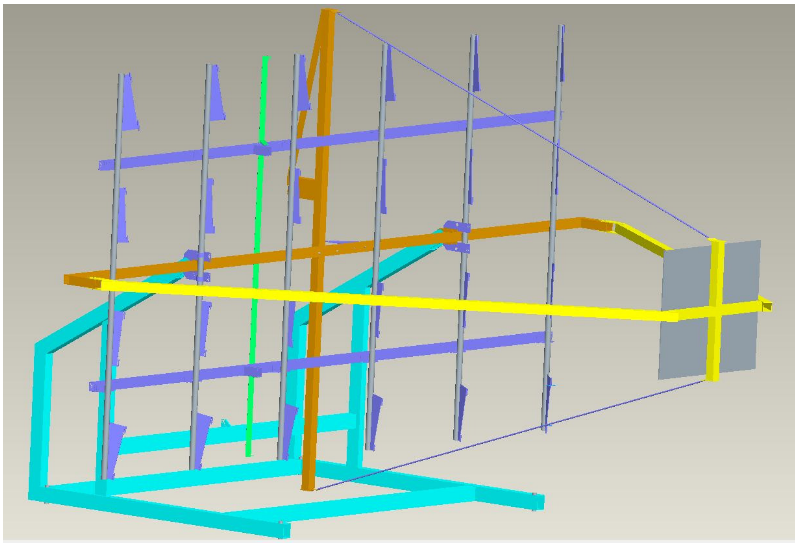

Figure 4: the mechanical structure on which the mirrors are mounted. At the right one can also see the support structure of the heat exchanger.

As shown in figure 5, the mirrors are all connected to each other, so that they can be rotated around their axes by only one motor. The angular velocity of each mirror can be adjusted by the length of its corresponding lever.

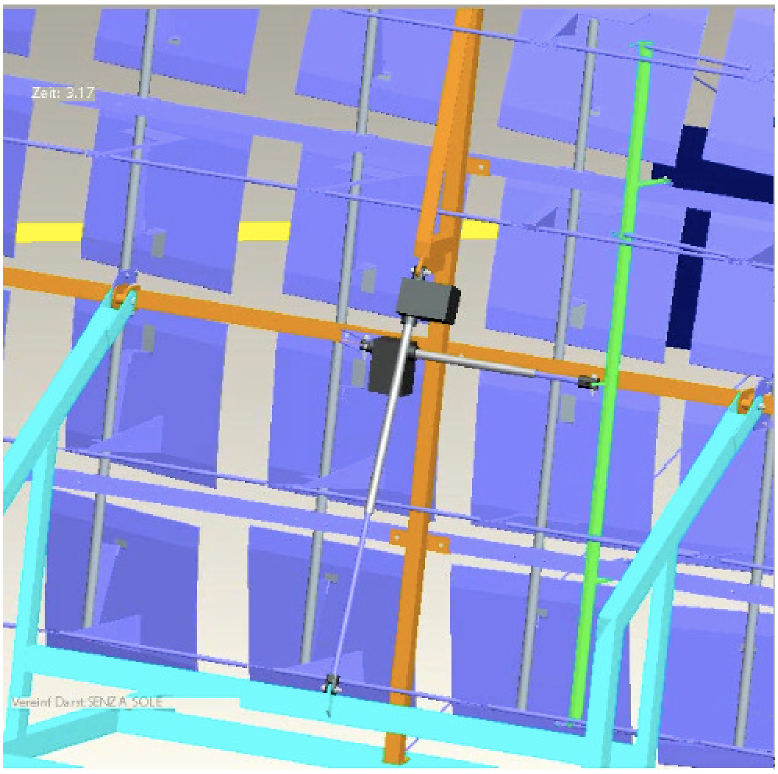

Figure 5: the mirrors are connected between each other and rotated around their axes by only one motor. A second motor adjusts the zenith of the whole mirror matrix and the heat exchanger.

Linear mirror performance

Each of the 24 mirrors of the current linear mirror system is 62 cm × 52 cm, for a total reflecting surface of 7.7 m^2. The heat exchanger has dimensions 86 cm × 62 cm for a surface of 0.53 m^2. During noon hours the heat exchangers creates a shadow on the mirror matrix, reducing the effective reflecting surface to 7.2 m^2.

In a first version, until February 2011, the heat exchanger consisted of a simple radiator, as it is used for heating homes. It was painted black with a heat resistant paint, as it is used for motors or exhaust pipes.

From the water flow through the heat exchanger and from the temperature difference between inlet and outlet of the heat exchanger we have determined the thermal power delivered by the linear mirror. A peak power of 4.0 kW was observed.

An independent measurement of the system was performed by the FfE (Forschungsstelle fuer Energiewirtschaft e.V.), Munich, www.ffe.de, and published in "Untersuchung eines solaren Spiegelsystems", T.Staudacher, T.Gobmaier, Auftragsnummer STMUG-06, Mai 2011.

The FfE measurement was in good agreement with our own measurements. Figure nn shows a figure of the FfE research report for the power achieved during one day.

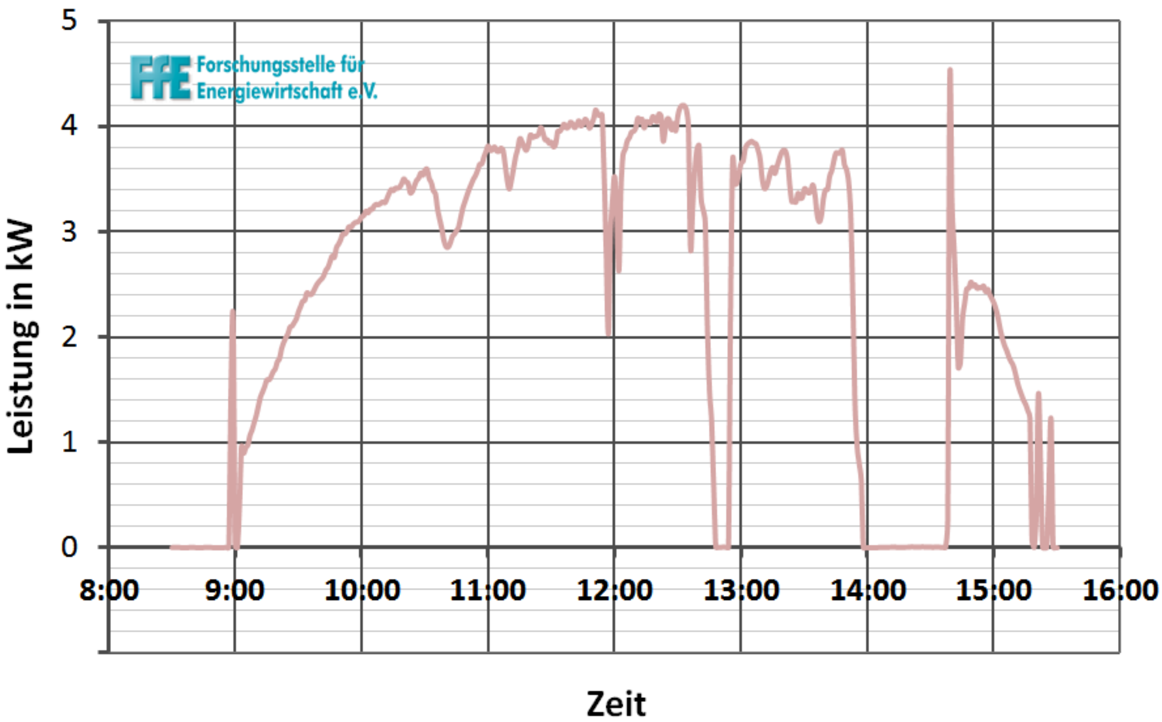

Figure 6: Power of the linear mirror system measured by the FfE research institute.

It has to be noted, that the FfE measurements were performed between end of November 2010 and March 2011 in Germany (Bamberg), in an exceedingly strong and cold winter. Still the linear mirror operated without any problems, heating water whenever there was sun.

As expected, providing high temperatures is no problem for the linear mirror system. The temperatures which we could achieve were actually limited by the boilers. We used boilers as are used for conventional solar collector systems, they usually have maximum allowed temperatures of 95 ºC. An example is shown in figure 7. The measurement stopped at 95 ºC (at the boiler inlet) in order to remain within boiler operating limits, but it is clear from the plot, that higher temperatures are possible with the linear mirror system.

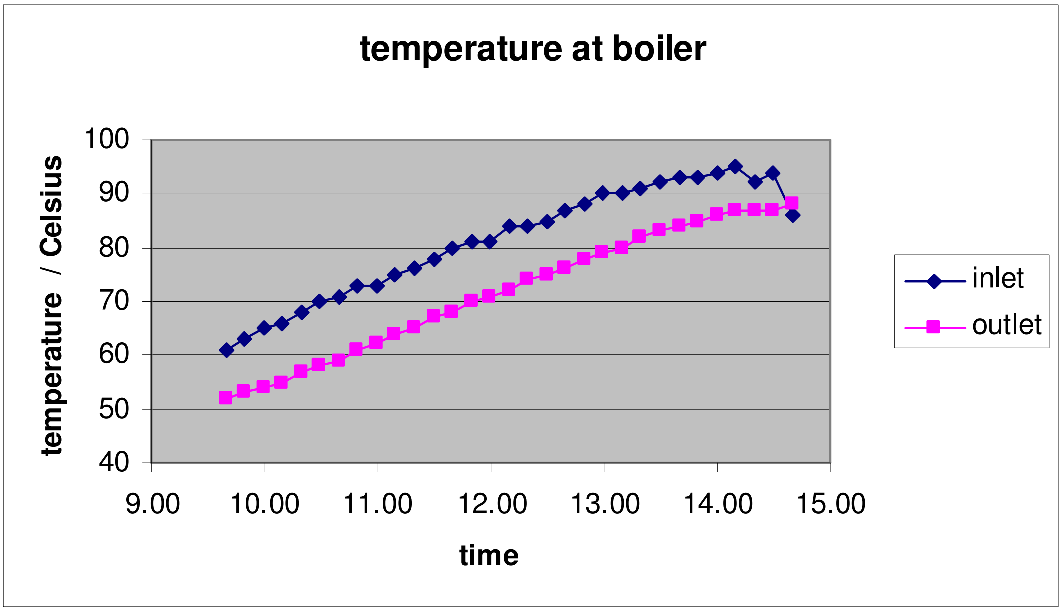

Figure 7: Water temperature at the boiler inlet and outlet during a typical day of operation of the linear mirror system (data taken in March).

Recently (Feb. 2011) we have started to use a new and improved heat exchanger, shown in figure 8. It is produced by the company Energie Solaire (Switzerland, www.energie-solaire.ch). It is made of stainless steel and has a selective absorber surface. It has a reflectivity for sun light of about 5%, (while it was about 20% for the radiator used previously) and has a reduced emission for heat radiation. It is Solar-Keymark certified.

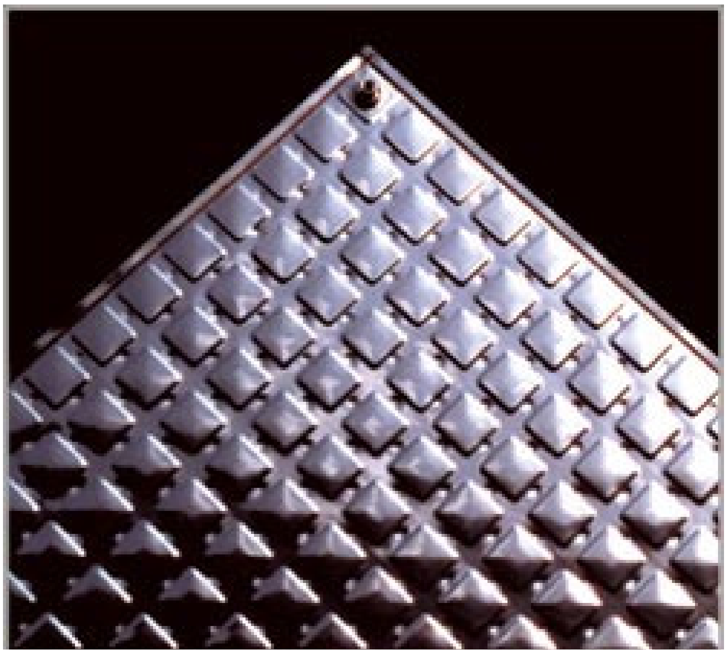

Figure 8 : the Energie Solaire Absorber with selective absorber surface used in the actual version of the linear mirror.

First measurements were performed with this new absorber. Some of hem are shown in figure 9. An improvement over the older, simple absorber is clearly seen. With the new heat exchanger the linear mirror now develops a power of up to 5 kW (before 4 kW).

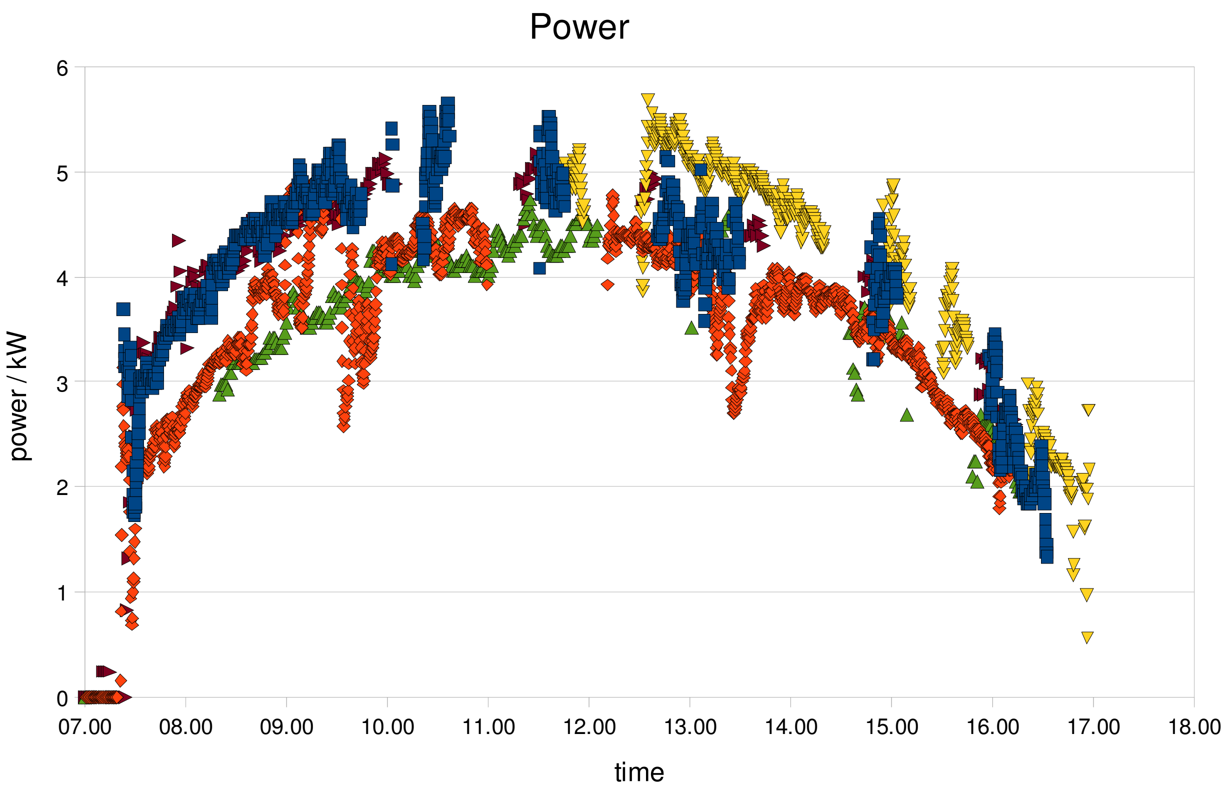

Figure 9: power delivered by the heat exchanger with the new selective absorber surface. Measurements from several days are shown with different colours and symbols.

The power is measured from the flow of the heat vector and the temperature difference between inlet and outlet of the heat exchanger. The main uncertainty of the measurement comes from these temperature sensors (up to 1˚C). Assuming that the true temperature difference is smaller than what was measured by 1 ℃, one results in a thermal power of 4.8 kW instead of 5 kW.

The heat power provided by the heat exchanger is equal to the incident power minus the heat losses. For the measurements of fig. 9, the heat exchanger was at temperatures between 60 ℃ and 70 ℃. At lower or higher temperatures the heat loss would be lower or higher, respectively. We have measured the heat loss by turning the linear mirror out of the sun, maintaining a flow of the heat vector at various temperatures. Measuring by how much the temperature of the heat vector decreases, we find the power loss. It is shown in figure 10. We observe a heat power loss of up to 350 W at a temperature of 90 ℃, and extrapolating to 100 ℃ we find a power loss of 400 W.
The ambient air temperature during this measurement was 28 ℃. Energy losses at different temperatures can be obtained also from fig. 10, since the energy loss is expected to depend only on the difference between ambient temperature and heat exchanger temperature.
Since now the difference between inlet and outlet temperature is quite small (not larger than 1 ℃), a dedicated high precision calibration procedure was applied for this part of our experiment. It consisted of bringing both temperature sensors in contact with water of the same temperature. The calibration we obtained from this procedure had an uncertainty of not more than 0.2 ℃ on the temperature difference between inlet and outlet sensor (not on

the absolute energy scale). This uncertainty results in an uncertainty of about 40 W on the scale of the vertical axis of fig. 10.
The measurements were performed at low ambient wind speeds (< 5 m/s). At high wind speeds the loss would increase, and could exceed also 1 kW for high temperatures.

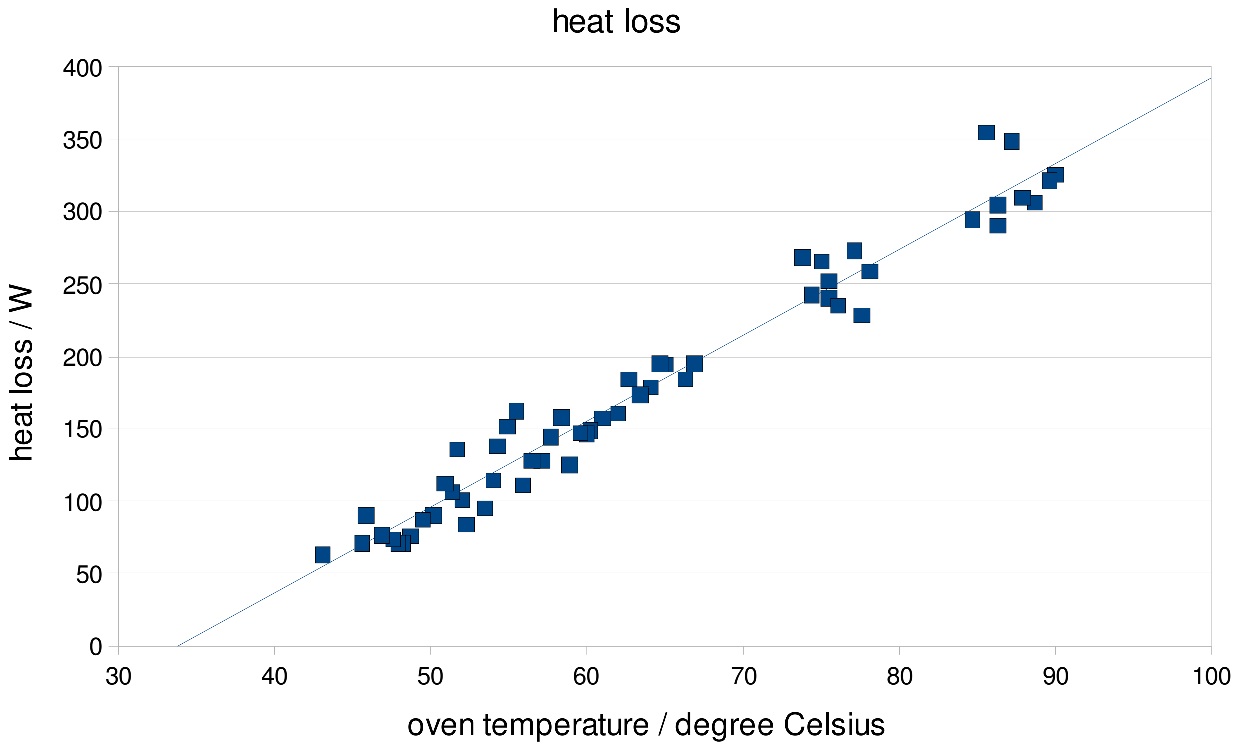

Figure 10: heat loss of the heat exchanger as a function of temperature. Outside air temperature was 28 °C.

The heat exchanger was not protected by a glass cover. Most of the heat loss measured in fig. 10 could be avoided by means of a glass cover. However, a glass cover would also absorb part of the incident radiation, depending on the quality of the glass it would absorb in the order to 500 W. Therefore it seems reasonable to operate the heat exchanger without a glass cover, as long as one does not exceed temperatures of 100 °C and as long as the heat exchanger is not exposed continuously to very strong winds.

Control System

Also for the electronic control system our priority was simplicity: the linear mirror is controlled by a PIC microprocessor. It reads the actual time from a clock, and reads the corresponding sun position from a lookup table. It adjusts the two motors accordingly once in a minute. Therefore the linear mirror always is in the correct position, even in cloudy whether.
The two motors consume at maximum 120 W, and they are never moved together, so we can control them over a simple pwm signal provided by an H bridge made from normal transistors, no special and expensive power electronics is needed. Since the motors run for a total of several minutes only during one day, and since the microprocessor also needs very little power, the total power consumption during the day is very low, in mean about 1 W.

At the time being the linear mirror is connected to the 230 V net, but for the future we want to operate it on a small photovoltaic module, 10 W of power should be sufficient.
The control circuit has up to 4 temperature sensors. Usually only two are in use: one for measuring the temperature of the heat exchanger, and one for the temperature of the boiler (the other two sensors may be used for monitoring purposes, if desired). If the heat exchanger gets too hot, or if the boiler gets too hot, the linear mirror turns its mirrors out of the sun, so that no sun light gets reflected onto the heat exchanger. Therefore overheating of the system in summer is excluded.
During the night the linear mirror moves into a protective parking position, lowering the heat exchanger close to the ground and mirrors facing the ground. In this parking position the linear mirror is protected against snow and hail. The mirror can be brought into this parking position also by a simple switch. In the future also a light sensor is foreseen to bring the linear mirror automatically into parking position, whenever there is no sun shine.
For the future a continuous increase of the intelligence of the control unit is foreseen, including an internet connection for communication. Also for this future development our goal will be to maintain the simplicity of the circuits, using only cheap microcontrollers with a very low power consumption.

Future

The larger part of global (and national) energy consumption is in form of heat, not in form of electricity. Therefore the linear mirror already in its present configuration – being used for heating water, but not producing electricity – can already make a significant contribution to reducing the use of coal, gas, oil and nuclear power.
Even without modifying the linear mirror itself, many new integrations are possible. For instance, the linear mirror is ideal for operating absorption refrigeration systems.
One can also install photovoltaic cells in the light spot of the linear mirror, for creating a concentrating photovoltaic system which at the same time can produce heat.
Of great interest would be a combination of a linear mirror with a seasonal heat storage system. A well isolated volume of 30 to 50 m^3 of water could be heated up in summer and provide heating for a home in winter, making the home totally independent of oil, gas etc.
But also the linear mirror itself can and will be further improved. For instance, by using more than 24 mirrors one can achieve much higher temperatures.
With a high temperature system one could operate steam turbines to produce electricity. In practice that would mean, that one could create the Desertec project in Europe, instead of the African desert, based on the linear mirror technology. That would not only save the long power lines from Africa to Europe. It also would allow to make use of the heat energy provided by the system, increasing the overall system efficiency.
We are therefore convinced, that the linear mirror is a good example for showing, that a transition from a society based on fossil and nuclear power to a society based on renewable energy is possible in an economic way. Of course, this cannot be achieved by the linear mirror alone, but only together with a variety of technical integrations. But the corresponding technologies exist already.
Note, that devices like the linear mirror can have a very long live time. The linear mirror consist essentially of aluminium and steel. After a few years, when the initial investment is paid back, the linear mirror will effectively produce energy for free. Therefore the linear mirror allows for a substantial growth of global economy without jeopardizing the environment.

Conclusion

The linear mirror is a readily available industrial product, which is heating homes and providing process heat at temperatures of up to 100 ºC, Though the industrial production of the linear mirror has started only three months ago, 200 kW of thermal power are already installed in Europe (May 2011).
The linear mirror is as simple to operate as conventional systems, like for instance solar collectors. But it is able to provide high temperatures also in winter, and it is able to protect itself against overheating in summer, and against being covered by snow and ice in winter.
The linear mirror is a solar system designed for the use in Europe.
Though the linear mirror offers already now many advantages, it can be further improved. First of all, many integrations of the existing linear mirror system are technically possible but have not yet been realized, like concentrating photovoltaic, solar cooling, or the combination of a linear mirror with a seasonal heat storage.
In the future, the temperature range of the linear mirror will be extended, covering almost all applications of industrial process heat.
All in all, the linear mirror is an example for showing, that transforming our energy consumption from fossil and nuclear to solar power is possible in an economically feasible way. And on a short time schedule