Birds resting on the receiver tube of a parabolic trough collector. A state-of-the-art parabolic trough mirror reflects more than 99.5% of the direct solar radiation on the receiver tube. Good receiver tubes stay cool outside due to the vacuum insulation.

Photos (3): Eckhard Lüpfer, DLR
Today’s parabolic trough mirrors are manufactured in tempered and laminated versions – and all made of glass. A fundamentally new concept now aims to replace glass with polymer films on an aluminium substrate. It could reduce costs significantly. Producers of glass mirrors view it with scepticism and claim a higher shape accuracy and durability for their products. The race for higher quality and lower costs has begun.

The actual competition is only just starting,” said Flabeg CEO Axel Buchholz in an interview for S&WE (see page 76). The rumbles in the market for parabolic trough mirrors are no longer to be heard. Two manufacturers still share practically the whole market for mirrors: the German-based Flabeg Group (around 50 % market share) and Rioglass Solar in Northern Spain (45 %). Both produce classic glass mirrors in a company-specific process. In 2008, the two were unable to satisfy the enormous demand of the CSP builders. In the meantime, the situation is completely different. The demand in Europe, in other words Spain, has stagnated since the approval processes were placed on hold (see S&WE 11/2009). The range of products available, on the other hand, has become wider and more diverse (see table on page 72). The US company Guardian, which also operates manufacturing facilities in Spain and Israel, has diverted capacity freed up by the dip in demand for automotive glass to solar mirrors. Flabeg has just inaugurated a new factory in the USA and expects this to raise the previous mirror output by a further 80 %, while Saint-Gobain Solar, with headquarters in Paris, has just opened a large production centre in Lisbon. And then there is the company SkyFuel from Colorado/USA, which has been pushing onto the market since 2007 with collector mirrors comprising silver-metallised polymer film laminated to aluminium sheets instead of silver-coated glass. But even that is not all – branch observers expect at least half a dozen further manufacturers to emerge in the coming years.

This atmosphere of upheaval and departure, and the inevitable conflict it brings, is one explanation for the harsh tone which reigns on occasions when representatives of these companies speak about each other. The statements of competitors, for example, are immediately showered with doubt to an extent which is rarely the case in the low-voltage solar thermal and photovoltaics sectors.

But at least there is a certain degree of agreement between the manufacturers when it comes to defining the properties of a good mirror. A good mirror
• reflects a high proportion of the sunlight (specular reflectance)
• onto the absorber tube with a high degree of accuracy (high shape accuracy and small specular beam diversion) and
• withstands the climate conditions of dry-summer regions and dry desert locations.

Taking the example of the Spanish power plant Andasol 3 (approx. 50 MW installed output capacity from 510,000 m² mirror area), the German Aerospace Centre (DLR) in Cologne has calculated that a 1 % higher reflectivity adds up to an additional electricity yield of €14 million over the course of a 20-year service life. Even if the equation is not quite as positive in the USA due to the less generous grid input remuneration, it is still worth investing in quality when the mirrors account for an 8 % share of the costs of a power plant.

The DLR experts should certainly know their business: after all, they have now been conducting research into solar mirrors for more than 30 years – since June 2009 at the “Test and Qualification Centre for CSP Technologies” (“QUARZ Centre”) in Cologne.

To facilitate assessment of the reflectance and shape accuracy of the different mirror types, the DLR has developed scientifically founded standards (Lüpfert, Ulmer 2009; Meyen et al. 2009), which have in the meantime achieved an international consensus. At the front line of the market, however, there is still work to be done to establish these standards. “The customers have been unaware of the quality differences and in the past purchased both good and poor mirrors for the same price,” says Eckhard Lüpfert from DLR.

Reflectance parameters

“Specular reflectance” defines the proportion of incident radiation which is directionally reflected by a mir-
Mirror manufacturing

<table>
<thead>
<tr>
<th>Company</th>
<th>Manufacturing process</th>
<th>Solar-weighted direct reflectance</th>
<th>Shape accuracy (FDx)</th>
<th>Production capacity per year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flabeg</td>
<td>grinding flat glass first ➔ hot sag-bending ➔ silvering ➔ coating ➔ gluing ceramic mounting pads</td>
<td>93.5 %</td>
<td>≤ 10 mm</td>
<td>2,500,000 mirrors</td>
</tr>
<tr>
<td>Rigglass</td>
<td>press bending at 620°C ➔ tempering ➔ gluing ceramic mounting pads</td>
<td>93.5 %</td>
<td>&lt; 10 mm</td>
<td>3,700,000 m² / 1,400,000 mirrors</td>
</tr>
<tr>
<td>Saint-Gobain</td>
<td>float glass process ➔ cutting ➔ press-bending at 600 °C ➔ tempering ➔ silvering ➔ gluing ceramic mounting pads</td>
<td>94 %</td>
<td>n/a</td>
<td>2,400,000 m² / almost 1,000,000 mirrors</td>
</tr>
<tr>
<td>Guardian</td>
<td>laminated mirrors: 1.6 mm low iron glass + PVB + 2.3 mm standard glass; ceramic mounting pads</td>
<td>95.2 %</td>
<td>&lt; 10 mm</td>
<td>&lt;600,000 m² / 250,000 mirrors</td>
</tr>
<tr>
<td>Skyfuel</td>
<td>multiple layers of polymer films with silver reflective layer (1.25 mm); drawn into edge guides of the collector frame on site</td>
<td>not applicable</td>
<td>not applicable</td>
<td>n/a</td>
</tr>
</tbody>
</table>

1 Flabeg does not promote tempered mirrors, but produces them on customers’ request; 2 also monolithic mirrors, 4 mm

The “solar-weighted hemispherical reflectance” indicates merely that proportion of the radiation which is reflected into the mirror hemisphere. After all, the important question is how much of the direct solar irradiation is actually reflected onto the absorber tube. That can be measured by way of a spot of light and its reflection. The DLR has specified an acceptance angle of 25 mrad (1.4°) for the standard. In other words, measurements include only the reflection from the mirror within the correspondingly defined cone. This proportion, the so-called “solar-weighted direct reflectance,” is a standardised parameter with which to judge mirrors with different surface properties. The researchers have even released the measurement data for four material samples which are described as “representative”. The solar-weighted direct reflectance of the examined aluminium mirrors lies at around 83.5 %, whereas silver-metallised polymer film achieves 87.4 %. Glass with silver back coating, on the other hand, returns a value of 93.9 % and thus serves as a yardstick for solar mirrors.

The DLR also tried to cover durability in connection with abrasion due to sand or dirt in the air and cleaning processes. The researchers used an abrasion instrument with a standardised grinding head which moves linearly across the sample. After 100 cycles, for example, the solar-weighted direct reflectance drops to 92 to 67 % of the original value (set as “100 %”) for an aluminium material, and even to 27 % for a silver-metallised polymer film. Silver-coated glass still displays a reflectance of 99 % after those same 100 cycles. The latest tests are now aimed at establishing comparisons with the actual influences encountered in power plant use.

Manufacturing process of Saint-Gobain’s Covilis plant in Portugal

1 Float glass is delivered in the form of 6 m by 3.21 m sheets
2 Cutting of each sheet into the parabolic mirrors’ final format
3 The edge-working process grinds away sharp edges
4 The glass is first heated up to 600 °C, then pressed into its final parabolic shape, before being tempered
5 Seized by a robot and placed on racks, the curved glass goes through the silvering line
6 As this thin silver coating needs to be sprayed on a surface completely free of any impurities, the glass is firstly polished
7 Applying protective varnish
8 The curved mirrors then go through another furnace where they are heated up to a temperature of 180 °C
9 Washed and then dried by blowing compressed air, each mirror is individually marked
10 Mirrors are installed on pallets, before being shipped to the Merida facility in Spain, where the gluing of ceramic fixing elements is done

Source: Saint-Gobain
Shape accuracy parameters

The deviation of the mirror surface from the geometrically optimum cylinder-paraboloidal form is the second factor which can diminish the proportion of incident sunlight reflected onto the absorber tube by the mirror. The parameters used to measure and describe such deviation are the “FDx” and “intercept” values. The intercept percentage derived from laser measurements provides a useful approximation, but tends to underestimate the deviation—not least because, by way of simplification, this concept generally assumes the rays of sunlight to be parallel. “The sun, however, is not a single point but an enlarged spot,” says Eckhard Lüpfert, who recommends instead the FDx value developed by the DLR as the more pertinent parameter for comparison.

One of the methods for determination of this value uses a digital camera to record a pattern reflected by the mirror. The cross-section through the mirror is a parabola with minor blemishes, the tangents of which form an angle with the parabola directrix. The researchers divide the mirror into 1 million imagined sections, each approx. 3 mm² in area, and compare the aforementioned angles with those of an ideal parabola. In this way, it is possible to calculate the distance in millimetres by which a reflected beam deviates from the ideal focal line at the axis of the absorber tube. The scientist figured out and proved that all the so determined deviations can be described very well by a Gaussian bell curve. So they decided to use the standard deviation FDx, an established statistical parameter, to describe the accuracy of the mirror shape by one single quality parameter. That means: statistically, an absorber tube with a radius of FDx would catch 68.3 % of the reflected rays, an absorber tube with a radius of two FDx close to 95.4 %, a tube with a radius of three FDx about 99.7 %. The DLR recommends an FDx value of not more than 12 mm for applications with 70 mm absorber tube diameter; an FDx of 10 mm is considered a good result.

In order to build an efficient solar plant, not only the manufacturing of the mirrors is important. A sophisticated and accurate mounting process on site is just as essential. The SkyFuel mirrors are delivered to the site of installation as rolls of aluminium sheet and, being just 1.25 mm thick, can be bent by hand before being forced into final shape upon insertion into the edge frames. Glass mirrors already acquire their form before they leave the factory. But even a glass mirror must still be fixed accordingly at the installation site to ensure that the form is not affected to an impermissible degree by manufacturing errors in the frame structure or wind loads. There are normally four ceramic pads bonded to the rear side, each incorporating a steel nut to which the mirror is screwed. By way of a suitable assembly process, tolerances in the substructure can be compensated in all three directions in space. For the three Andasol power plants, and 30 other Spanish projects, the so-called “Eurotrough” concept was used for this purpose. Could suitable adjustment be an elegant means
Properties of mirror types: controversial positions

The DLR measured a solar-weighted direct reflectance of 93.9% for glass mirrors and thereby confirmed the figures quoted by the three main suppliers. Guardian even specifies 95.2% for its two-layer laminated mirrors, and backs up this claim by explaining that the sunlight must only pass through the upper 1.6 mm glass layer, and not through some 4 mm as in the case of monolithic mirrors. Jordi Villanueva from Rioglass acknowledges the higher reflectivity of laminated mirrors, but also expresses his reservations: “The accuracy of the shape is very difficult to achieve. And in the future there may be delamination problems.”

For the new film-on-aluminium-collectors, measurements are quite controversial. For a silver-metalised polymer film, the DLR measured a solar weighted direct reflectance of 87.4%, but does not relate it to a certain manufacturer. SkyFuel claims a reflectance of 94% for its films. To underline their data, SkyFuel names Cheryl Kennedy from the National Renewable Energy Laboratory (NREL) in Colorado as the source, the US counterpart to the German DLR. It is currently difficult to quantify the influence on direct reflectance to be expected from abrasion due to cleaning processes or sand and dirt in long-term operation in the field. The DLR is to date only able to make relative statements. Christopher Huntington from SkyFuel says that “scratches occurred only with older versions of the film when treated with rough measures” and goes on to point to ten panels at the SEGAS VI power plant at Kramer Junction, California, which have been installed since 2002 “without a problem – the reflectivity has not been effected.” Huntington also cites a conference paper presented by SkyFuel and the NREL in July 2009. This paper (DiGrazia, Gee, Jorgensen 2009) contains an in-depth discussion of various tests on weathering resistance, though none on abrasion.

If the debate on durability is to end positively for SkyFuel, then the cost argument put forward by Christopher Huntington will gain weight: “Our solar collector assemblies cost approximately 30 percent less to build than the collectors at Nevada Solar I which use glass mirrors (from Flabeg, ed.).” In reply to enquiries, he adds by way of precision: “With solar collector assembly I mean mounting, pylon, space frame, mirrors and receiver.” On the other hand, SkyFuel has not yet been required to prove that it is actually able to supply collectors for power generation at a reduced price of this order, because only prototypes exist to date.

The four glass mirror manufacturers are naturally viewing the SkyFuel concept with great scepticism. The standpoint of Rafael Sanz de Acedo Hecquet is representative for all four: “Saint-Gobain has a division dealing with plastics. (...) We could have developed a plastic reflector ourselves, but because we know (...) the behaviour of this solution, we prefer to propose glass mirrors to the market. (...) Banks feel more comfortable with them.”

The durability of mirrors is also a subject of passionate argument within the glass mirror fraction. All have (also) tempered mirrors in their portfolio – with the exception of Guardian, which is in turn the only manufacturer to recommended laminated mirrors, i.e. products comprising a thin mirror bonded to a thicker glass pane by way of a polyvinyl butyral (PVB) film.

Jordi Villanueva from Rioglass justifies the tempering of the mirror glass as follows: “Tempered glass is five times stronger than a non-tempered or laminated piece of glass. The mirrors have a form memory. One can bend them flatly to the ground, but they go back to the original form.” Michael Magdich, General Manager of global CSP & CPV at Guardian, on the other hand, seems to have gathered contrary experience from over 40 wind tunnel tests: “Because Guardian mirrors are laminated, they dampen natural vibrations in severe weather conditions and thereby resist breaking. Monolithic broke at 80 mph in the wind tunnel – laminated cracks above 130 mph. Although stronger to static stresses, tempered is very susceptible to sharp impact.” And once a tempered mirror breaks up, this could lead to a domino effect. “One broken mirror will release 200,000 4-gram pieces of glass. Each of which if travelling at 90 mph could break another mirror.”
Rioglass Spokesman Villanueva cannot let that stand unanswered: “Each mirror weighs an average of 28 kg (28,000 grams). Therefore, if you divide 28,000 grams by 200,000 pieces, then each piece weighs an average of 0.14 grams. By far not enough to cause any damage on a tempered mirror, even if it flies at a very high speed.” Both opponents would gladly go further into detail with their arguments.

One could be forgiven for thinking that solar power plants are threatened by wide-scale glass breakage on a daily basis. But the subject causes much less of a stir at Flabeg, which has so far neither tempered nor laminated its glass: “We see a breakage rate of 0.027 % for non-tempered solar mirrors from Flabeg in the field. This is borne out by our latest experience with the CSP project Nevada Solar One.”

Robert Cable, Plant Manager at Nevada Solar One, confirms this figure. Even though the new factory in the USA will be manufacturing also tempered mirrors, Flabeg’s basic philosophy remains unchanged. “We expect some of the state governments to prescribe safety glass for CSP applications. Our focus, however, will remain on non-tempered solar mirrors.”

The big issues in the future will definitely be efficiency, price and the ability to deliver, and the race is still open. Solar Millennium AG chose Flabeg mirrors for Andasol 1 and 2 – but the supplier for Andasol 3, where construction began in September 2009 is Rioglass. Yes, indeed, the actual competition is only just starting.

Alexander Morhart
“The actual competition is only just starting”

Until now, the German manufacturer Flabeg has been the undisputed market leader for parabolic trough mirrors. But the market is growing and so is the competition.

S&WE: Mr. Buchholz, how large is Flabeg’s share of the market?
Axel Buchholz: We are the market leaders, and I would say that our market share is currently something over 50 %. Our biggest competitor at the moment is without doubt Rieoglass in Spain.

S&WE: Rieoglass also is a producer of glass mirrors. Buchholz: Exactly. At present, all the power plants are equipped with glass mirrors – or should I better say reflectors, to remain neutral.

S&WE: The US company SkyFuel now has an aluminium trough with a multiple-layer film.
Buchholz: All I can say to that is that this product is still not to be found in practice, is still to be sold anywhere and, according to our measurements, is still far from living up to the manufacturer’s claims – not to mention the specifications which need to be met.

S&WE: So you have tested it yourself?
Buchholz: We have tested it, yes.

S&WE: Which are the criteria which you find are still to be satisfied?
Buchholz: There are two key aspects here, namely the reflectivity or reflectance, on the one hand, and the shape accuracy, i.e. the precision of the curvature, and also the surface of the reflector, on the other. The better the values for these parameters, the higher the efficiency of the solar power plant.

S&WE: You specify a reflectance of over 93 % in your data sheets.
Buchholz: With 4 mm thick glass, we are in the meantime – since two or three months – able to guarantee 93.5 % on average; in reality, we are already somewhere between 93.5 and almost 94 %.

S&WE: That is a surface property, so to speak. Then there is the precision. What about shape accuracy?
Buchholz: The shape accuracy we are talking about means that we are able to hit the centre, i.e. this 70 mm band, with a reliability of at least 99.5 %. Here, too, we are actually already supplying one generation ahead with even higher precision.

S&WE: But most of the sales are 4 and 5 mm thick mirrors, so we are talking about different figures there.
Buchholz: Yes. Around 90 % of the mirrors we sell are 4 mm, but a few customers choose 5 mm for the outer mirrors, because the greater stability of a thicker mirror is more favourable for the higher wind loads that are sometimes encountered in those positions.

S&WE: The product is one thing, but costs are naturally another matter. What is happening on that front?
Buchholz: The costs are naturally determined firstly by the raw glass costs. They are quite favourable at the moment, but will no doubt pick up again in future once the capacities for the overall world glass market become scarce. That is one factor. At the same time, both on the raw glass side and for us: we are working with relatively energy-intensive processes, with the furnaces we have to keep heated, and so energy costs are also significant. And let’s not forget the other raw materials such as silver and radium which are used in the coatings. And of course the labour costs – though admittedly we are not very sensitive to increases in labour costs, because our process is highly automated. That is all one story. Another story with a massive impact on costs, and thus on prices, as we can already witness, is that of the economies of scale. In other words, as we develop from a niche market into a broader specialist market, with constant growth rates of 20 to 30 % per year, there is a whole new dimension of cost reduction potential which can be realised.

Axel Buchholz, 46, has been guiding the fortunes of the Flabeg Holding with headquarters in Nuremberg for the past seven years. As CEO, he spoke to us about the company’s market leadership in the field of CSP trough mirrors, about cost developments and about the competition.
S&WE: Can you put that into figures?
Buchholz: We started in 2005 with a capacity of 200,000 mirrors per year. We then increased that to 800,000 mirrors in 2007, to 1.4 million by the end of 2008, and the new factory in the USA will give us a total capacity of 2.5 million units, let’s say from the beginning of next year. And we also have everything prepared for the addition of another 800,000, but we are holding back there at the moment because there is simply too little demand for European projects due to the current situation in Spain.

S&WE: How have the mirrors changed since the early 1980s?
Buchholz: Placing the reflectance and shape accuracy in the foreground, not that much actually. The reflectance is up by around 2.5 percentage points in the meantime, and the shape accuracy – I would guess, although it’s difficult to say really – has improved by perhaps 5 to 10%. Otherwise, with regard to the composition of the coatings, for example, everything is very much the same as in the past.

S&WE: Saint Gobain is building a big new factory in Portugal, according to their own announcement the biggest in the world. Do you think there is room for everyone on the market – or is the situation now getting a little crowded?
Buchholz: First of all, we already have significantly greater capacities at our facility in Furth am Wald than what they are installing over there. And secondly, we are not particularly worried anyway. If the developments come as we expect – for the moment disregarding the locally specific Spanish issue which is on the table at present – then the market will be large enough for us all. There was a similar discussion at the “Solarpaces” conference. The topic of capacity bottlenecks for core components, the Damocles sword which was hanging over the branch a year or so ago, is not a matter of concern today. We have sufficient capacities for the core components, and that applies not only to the mirrors, but equally to the receivers or absorber tubes.

S&WE: Does that mean that the actual competition is only just starting?
Buchholz: You could put it that way, yes.

S&WE: So are the prices going to drop? After all, we saw quite drastic cuts in the PV industry, after the Spanish PV market collapsed.
Buchholz: There will no doubt be a certain pressure put on prices. I cannot see things becoming as dramatic as in photovoltaics, but there will be pressure on prices, of course.

S&WE: Which proportion of the investment costs for a parabolic trough power plant are accounted for by the mirrors?
Buchholz: Around 5 to 7 % of the total investment sum, depending on whether the plant includes accumulators or not.

S&WE: That is a relatively small contribution to investment costs. Are there any other components where you think the effects will be greater?
Buchholz: No, I think everyone must do their homework. The whole CSP process must prove that it is able to reduce the present costs by 20 to 30 %, and all the components have a contribution to make. We, too: we are today selling our mirrors at prices around 30 % lower than two or three years ago. And we also see no problem in taking a further 10 or 15 % off the prices in the medium term, provided our production capacity is being utilised accordingly. And at the same time, we are working to boost efficiency by, let’s say, easily 5 or even 10 %. If you add that all up, then we are already doing our part. But everyone must do the same.

S&WE: When a company joins the branch as a newcomer, what is the particular difficulty with the product “parabolic mirrors”?
Buchholz: Shape accuracy. Given the methods used by other competitors, we are certain that they cannot attain the shape accuracy which we offer. And over the whole 20 years of a project, that could well make a difference of several million euros for the customer.

S&WE: What do you expect from the next few years?
Buchholz: We want to secure our market position as a basis for expansion, especially in the international field. In other words: a process of business internationalisation, for which America has been the first step. And in the medium term, the aim is to be able to supply the whole world from local and regional production facilities – in precisely the same way as we now do in the automotive sector. We will also be working on product optimisation – both mirrors and field systems – as our contribution to what will hopefully be the sustained market success of CSP as an alternative technology, because that is of course in everyone’s interest.

The interview was conducted by Eva Augsten.