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Messkampagne Photovoltaik Schallschutzanlage Münsingen

Monitoring und Betriebserfahrungen der ersten bifacialen PV Schallschutzanlage an einer Bahnlinie der SBB in Münsingen BE

Auftraggeber:
Bundesamt für Energie BFE
Forschungsprogramm Photovoltaik
CH-3003 Bern
www.bfe.admin.ch

Kofinanzierung:
Space Energy, Kanagawa, Japan
TNC Consulting AG, CH - 8706 Feldmeilen

Auftragnehmer:
TNC Consulting AG
General Wille-Str. 59
CH-8706 Feldmeilen
www.tnc.ch

Autoren:
Thomas Vontobel, TNC Consulting AG, vontobel@tnc.ch
Thomas Nordmann, TNC Consulting AG, nordmann@tnc.ch
Luzi Clavadetscher, TNC Consulting AG, clavadetscher@tnc.ch

BFE-Bereichsleiter: Dr. Stefan Oberholzer
BFE-Programmleiter: Dr. Stefan Nowak
BFE-Vertrags- und Projektnummer: 154209 / 103195 - SI500361
Installationsstandort Schallschutzwand Bahnhof Münsingen, 609 107/191 612

Für den Inhalt und die Schlussfolgerungen ist ausschliesslich der Autor dieses Berichts verantwortlich.

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Abstract

The world's first bifacial PV noise barrier plant on a railway line went online end of 2008 in Münsingen, Switzerland. 2009 the PV plant was fully equipped with measurement instruments in order to monitor functionality of the bifacial PV noise barrier plant during first years of operation, evaluate performance, overall energy production and influence of shading on bifacial PV plants. A focus of investigation was on shading effects on an operating bifacial PV plant, especially caused by railway infrastructure.

A maximum performance of up to 75% was measured, leading to a total energy production of 5'076 kWh in 2010 and 5'339 kWh in 2011 with very similar solar irradiation in these years which were about 13% below simulation-based expected solar irradiation for Münsingen. With a nominal power on the front side of the bifacial modules of 7.25 kWp this leads to a specific performance of 700…736 kWh/kWp. Corrected to average solar irradiation this leads to a specific performance of 790…830 kWh/kWp. This is still less than the expected 931 kWh/kWp.

Shading of one string during morning hours leads to a reduction of energy production of 60% during the shaded morning hours for this string. For the overall energy production of the plant, this corresponds to a reduction of slightly more than 5%. Further reduction is due to inverter sizing and efficiency, which is partially due to unequal front and back side nominal power of the bifacial modules. Optimal front-to-back-ratio of the bifacial modules and inverter sizing is accountable will presumably lead to another 5…8% additional energy production.

The overall performance of the bifacial PV noise barrier plant in Münsingen is good so far, although there is some potential for further improvement.

Description of situation

Introduction

On the important North-South railway line Bern-Lötschberg in Switzerland, the world's first bifacial Photovoltaic plant integrated in a noise barrier along the railway has been realised in December 2008. For this project, the originally planned noise reflecting transparent noise barrier elements have been substituted by bifacial PV modules based on a special glass-glass-structure to fulfil the noise protection requirements. Economical considerations such as the substitution of conventional glass noise barrier elements by PV modules fulfilling the noise protection requirements can be studied with this pilot project as well as technical questions concerning the use of bifacial PV modules in a noise barrier along a railway line. Different issues concerning the operation of bifacial PV noise barriers shall be evaluated by comparing several years of operation of the different bifacial PV noise barrier plants on the railway in Münsingen and on the highway in Zürich.

Figure 1: The PV plant consists basically of two adjoining noise barrier sections, marked and labeled with Noise Barrier 10 (LSW10) for the section, which starts directly at the north end of the train station, and the section Noise Barrier 7 (LSW7), which starts at the north end of the LSW10. This results in a total area of 115m² available for the PV noise barrier elements for a given height of 1m.

The 115m² noise barrier section results electrically to a total nominal power of about 7.25kWp for the front side of the bifacial modules (higher cell efficiency), or a nominal power of a little more than 5.6kWp for the backside of the bifacial modules (lower cell efficiency). Electrically, the plant is split up in 3x2 groups, each group with 7 or 8 modules. Two identical groups are combined to one inverter. This allows the side-by-side comparison of two groups of modules under real operating conditions in order to answer some of the questions concerning the influence of partial shading by the rail infrastructure, the temporary shading of passing trains or the influence of dirt deposits on the overall yield of the plant. By using three small one-phase inverters instead of one larger three-phase inverter, the possibility of making side-by-side comparisons of the inverters under real operating conditions has been preserved.

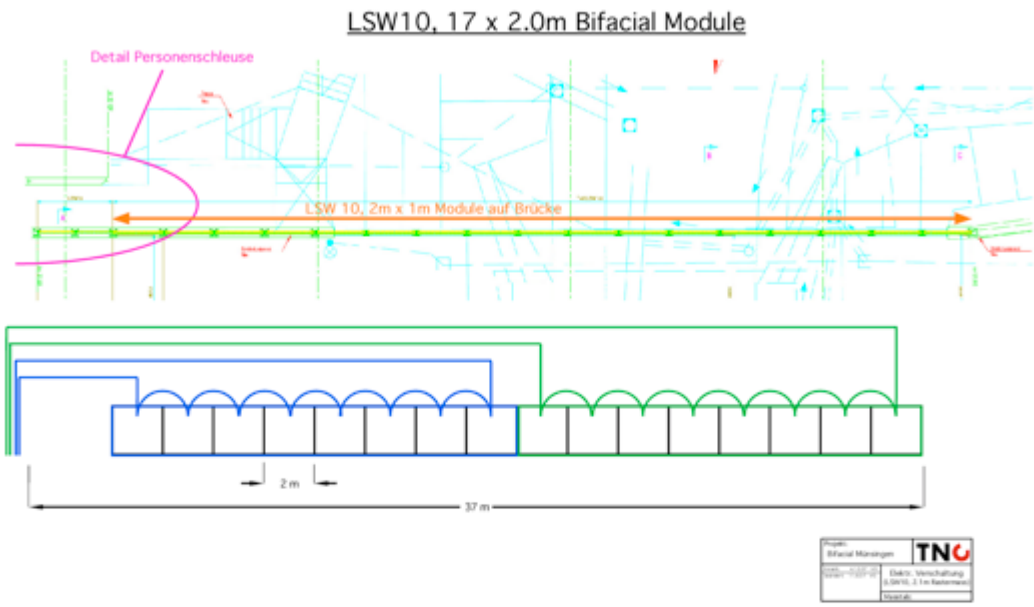

Figure 2: Array layout of the noise barrier section labeled LSW10. Section LSW10 consists of 2 strings of modules on the bridge crossing the road, which allows a comparison of these non-shadowed groups as reference, and share one inverter. The modules in this section are of different dimensions and nominal power than the other modules due to static limitations given by the bridge construction.

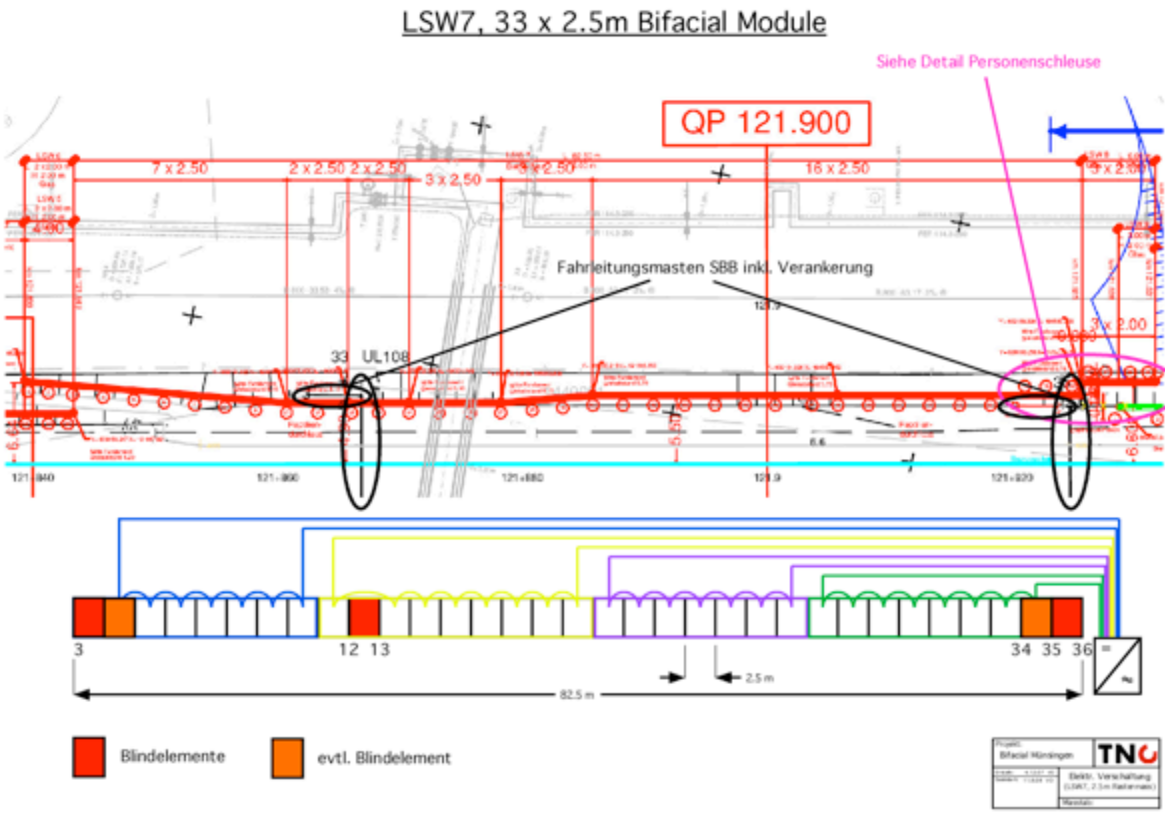

Figure 3: Array layout of the noise barrier section labeled LSW7. Section LSW7 consists of 4 strings of modules. The blue and the green string (8 modules) make up one array with an inverter and the yellow and violet string (each 7 modules) make up the second array of LSW7.

Project aims

Influence of shading

Shading for bifacial PV noise barriers can be even more delicate than for on-roof PV systems. The vertically (high tilt angle) arranged PV modules are more susceptible to shading at low elevation of the sun. During high sun elevation over midday, the bifacial modules as arranged in the noise barrier in Münsingen can use only small amounts of the solar irradiation for power production.

On the other hand, shading will never occur on both sides at the same time, allowing the non-shadowed side of the bifacial PV module to absorb at least the indirect irradiation.

Different causes for shading

Shading can occur due to topographical reasons, objects or obstacles such as buildings or vegetation in close proximity and in the case of PV on railway lines through railway infrastructure. The influence on the yield of typical railway infrastructure, such as shading from transmission lines shall be explored. This is achieved with comparison of PV arrays with different shading conditions.

Measurement

Measurement equipment

The measurement equipment was installed in May 2009 by TNC. It contains meteorological data, especially solar irradiation and ambient temperature, DC values on the level of strings and AC values on the level of the inverters for the module arrays.

All sensors are connected to a data logger, which stores the input values. First calculations are done by the data logger, based on a customized logger program developed and written by TNC for the bifacial PV plant in Münsingen. The data on the data logger is collected regularly by TNC using a GSM modem connected to the data logger for remote access.

Figure 4: Installation of the three temperature compensated reference cells. Two are parallel to the modules facing east and west, one facing south with 35◦ inclination.

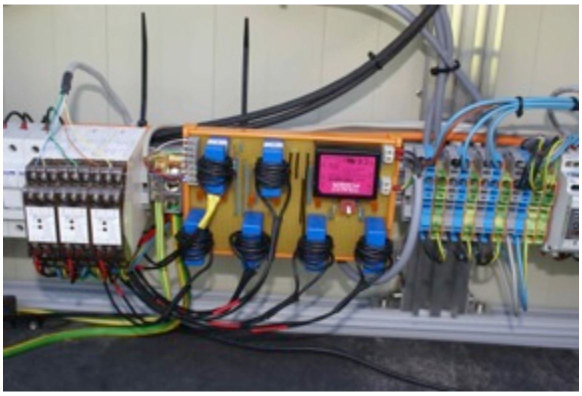

Figure 5: Each group of modules has one Hall sensor measuring the DC current (blue on the orange print). To the left the three DC voltage measurements of the PV arrays are installed.

Figure 6: The data logger stores the input data and does basic calculations based on a customized logger program developed by TNC. The data logger has a separate power supply including a battery backup system to prevent data loss in case of power outage.

Values and time resolution

In the middle of the northern section LSW 7 of the noise barrier three temperature compensated reference cells were installed. Two reference cells are installed parallel to the modules, one facing east and the other facing west. The third reference cell is facing south with an inclination of 45°. This allows the comparison of the solar irradiation of the two sides to the east and the west in comparison to a south oriented plane. In addition there is a temperature sensor that is located with the three reference cells for the measurement of the ambient temperature.

To measure the electrical parameters of the PV plant, 3 DC voltage measuring units have been installed, one before each inverter for the 3 arrays. Every inverter is fed by two strings of modules in parallel, consisting of the same amount of modules of the same dimensions and type. Each of these groups of modules has a Hall sensor to measure the current on the DC side. This results in 6 DC current values and a DC energy calculation for the modules. In addition one single phase AC energy meter is installed per inverter on the output side of the inverter.

The first full year of measured data was acquired in 2010. Now with the data of 2011 and 2012 available, comparisons can be made. In addition TNC has the possibility to access the data of the bifacial PV noise barrier plant on the highway in Zürich for further comparison on a longer timescale.

In 2011 the Software on the data logger was expanded for more detailed analysis based on a higher time resolution. This was done with the aim of achieving a more precise analysis of the facts already found in the first year of the measurement campaign for confirmation and more detailed analysis. This data is currently under evaluation. Some first results are shown in the following chapter.

Overview of results

Based on the experience from the bifacial PV noise barrier plant in Aubrugg and several other PV plants, a calculation of the expected yield was done by TNC based on the simulation of the solar irradiation and the technical specifications of the components used in the bifacial PV noise barrier plant. The expected yield was calculated at 6′ 750 kWh/a. This corresponds for a nominal power measured for the front side of the bifacial modules of 7.25 kWp in a specific yield of 931 kWh/kWp. For east/west facing and vertical structures, this would be a very good result and comparable to conventional, south facing PV plants in similar conditions in Switzerland.

Overall power production

The measured yield of the plant for 2010 is at 5′076 kWh, for 2011 at 5’339 kWh and for 2012 at a measured value of 4’078 kWh.

The measured solar irradiation in the sum of both planes of the PV modules for 2011 is at 1’266 kWh/m^{2}a. This is just a little below the solar irradiation of 2010, which was at 1’286 kWh/m^{2}a. Compared to the simulated solar irradiation of 1’455 kWh/m^{2}a the year 2011 was below the standard meteorological year (87%) for the special case of the east and west oriented, vertical planes of the bifacial PV noise barrier plant in Münsingen. One additional challenge for evaluation of standard meteorological years is the accuracy of the simulation tools available for the conditions applicable for bifacial noise barriers. Module tilt angle of 90° and orientation east and west is unusual for solar irradiation simulations in the area of photovoltaics. Topographical information has to be taken into account for the low sun elevations, which is only done in the newer developments of the simulation tools (MeteoNorm was used here, starting with v5 and then v6 until newest v7 takes topographical information into account).

Performance of the arrays lies between 62.5% and 75%. 75% is a fairly good value, which is reached on the front side during morning. Performance is evaluated by plotting the normalized AC output against solar irradiation. For normalizing, the nominal power of the front side of the bifacial modules is used. One of the reasons why state of the art performance values of 80…85% are not reached is the slightly too large inverters. They are operated mainly in partial load, leading to reduced inverter efficiencies.

Inverter efficiency of the SunTechnics STW 1400 respectively STW 1900 is nominally at 91.4%, respectively 92.4% (EURO efficiency). The SunTechnics STW inverters are based on the Fronius inverters. Measured operational inverter efficiencies vary between 84% and 91.7% in normal operation conditions. During months with lower solar irradiation in winter, the inverter efficiencies are even lower, resulting in overall average inverter efficiencies of around 77%. With ongoing improvement in inverter technology, a improvement of the overall performance of the bifacial PV noise barrier should be possible.

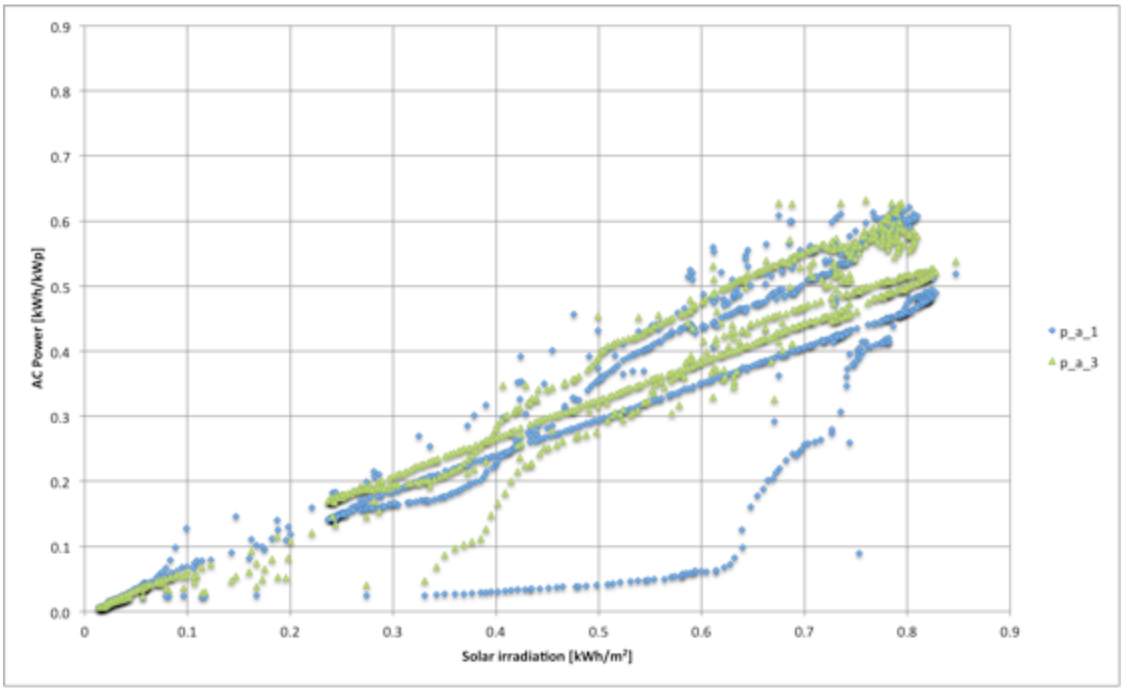

Figure 7: Evaluation of the performance for two arrays (arrays 1 and 3, normalized AC power output p_a_1 and p_a_3) show clearly the two lines depicting front and back side per array. Performance of between 62.5% and 75% is reached for front and back side.

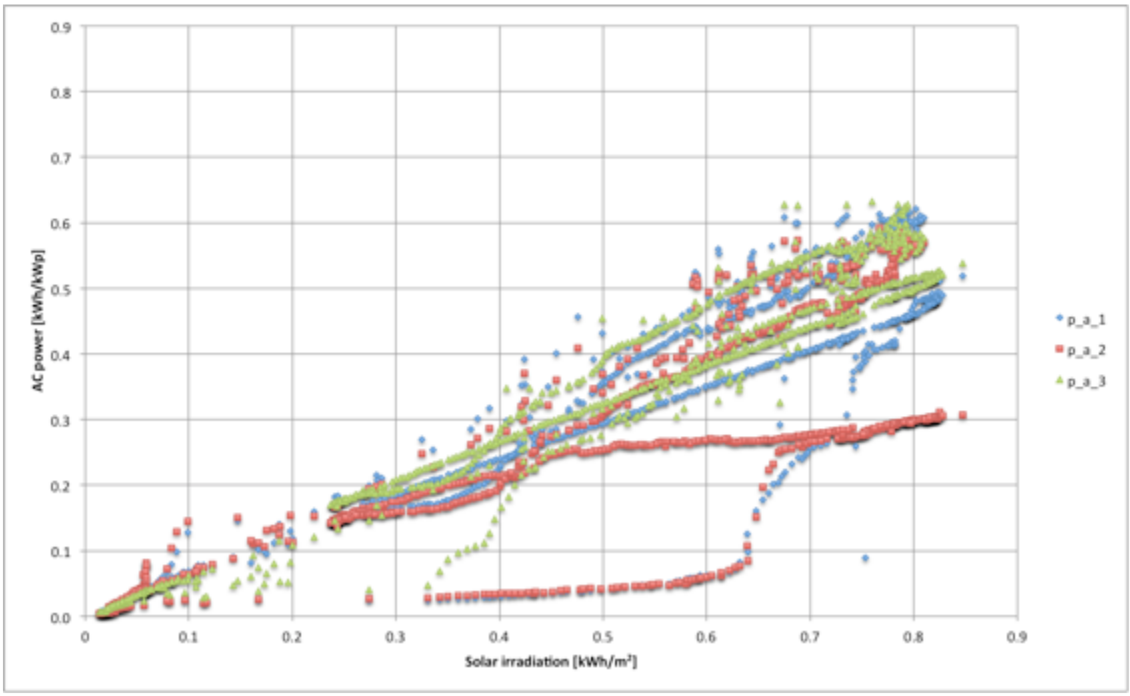

Figure 8: The performance of the third array (p_a_2 in red) shows behavior of shading leading to a highly non-linear behavior in the normalized power output. The reasons for the shading are further investigated later on.

The performance of the bifacial PV noise barrier plant in Münsingen is good. Adjustments and optimizations can further improve the performance of the PV plant. If solar cells are available with better front-to-back-ratio, the overall performance can be further improved by estimated 5…8%.

Shading

Trees in direct environment of the north end of the PV plant

The influence of the shadowing of the east side of the northern most part of the bifacial PV noise barrier due to the adjacent trees has already been shown in the measurements of 2010. With the more precise measurements now available based on the 1 minute measured data, this influence has been re-evaluated. While the hourly data led to the calculation of the measured reduction of 65% of the yield for the affected string during the morning hours, the new data shows that this reduction is slightly lower at about 60%. Counter measures have been discussed with the municipality, but they are too drastic, so the lower yield is accepted. The influence on overall energy production is based on the power-weighted share of the shaded string slightly above 5%.

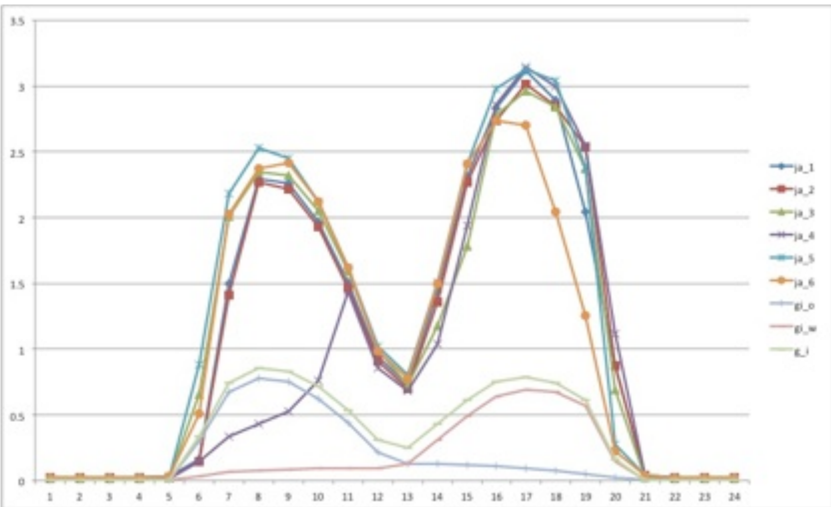

Figure 9: Based on the hourly data, a first estimation of the influence of the shading of the northern most string of the bifacial PV noise barrier plants was made at approximately 65%. For this, the DC current of the module groups (ja_1…ja_6, [A]) have been compared taking into account the solar irradiation east (gi_o) and west (gi_w).

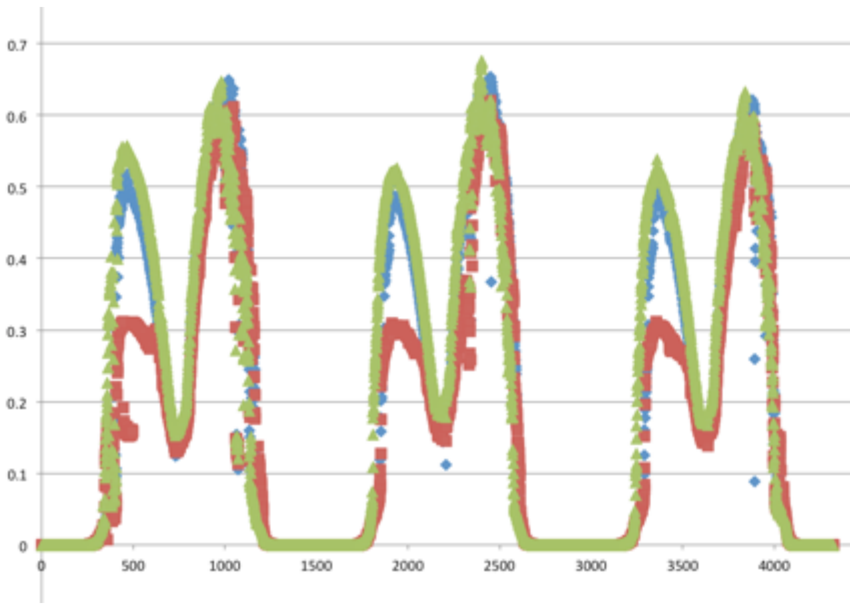

Figure 10: The more precise data measured in 1 minute steps allows a more precise estimation of the reduction of the yield of the string affected by shadow in the morning hours at about 60% reduction. For this, the normalized AC power output has been used, similar to the evaluation of the performance shown in Fig. 7 & 8.

Influence of railway infrastructure

In places where shading through railway infrastructure was clearly dominant, dummy PV modules have been inserted. This is the case in two places where a power line pole is standing in front of a PV module.

Figure 11: The PV module behind this powerline pole is a dummy module, since shading will be permanent and covering the full module area.

Figure 12: The PV module on the right side behind the powerline pole is a dummy module. On the East side there is also shading due to the passageway construction to the right of the module.

The concept of proving the influence of shading on the performance with the available data was tested for the shading occurring during morning hours. This effect can easily be separated, since the reason is very clear for the string at the north end of the plant and can be compared to the modules on the bridge, where there is no shading during morning hours. The results show that the data available is quite precise, reflecting the different nominal powers of the strings and the influence of the shading by trees in the north clearly.

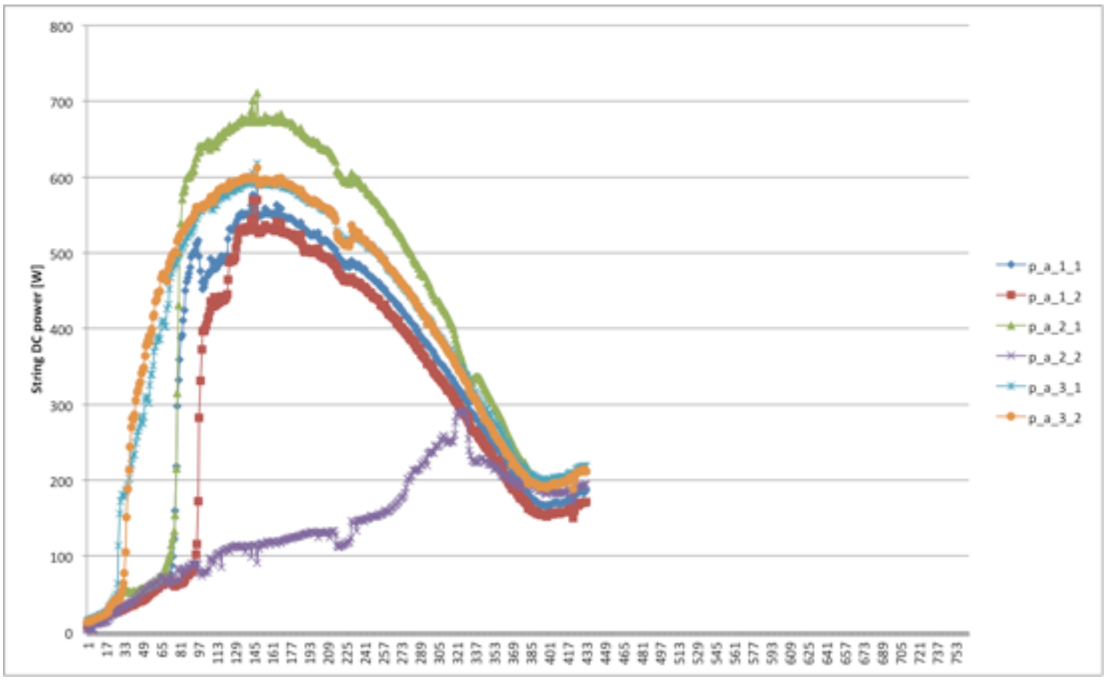

Figure 13: DC power for the different strings during morning hours on a sunny day. Different nominal power ratings of the arrays are visible. The two strings within one array (for example p_a_3_1 and p_a_3_2) show the same DC power production. String 2 in array 2 (p_a_2_2) is the north most string with shading by trees.

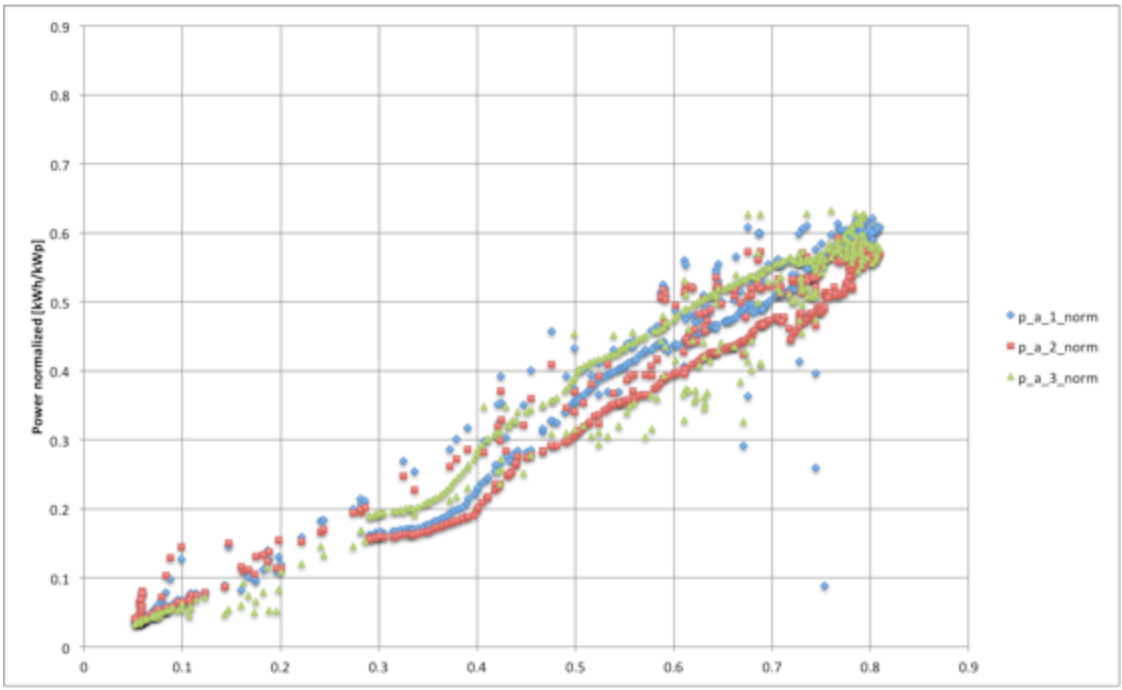

Figure 14: All arrays apparently work fine with similar performance of around 75% during afternoon hours without shading from trees during this example day (1st August 2011).

Partial shading of the infrastructure of the railway line is shown below. During planning phase, lightning poles could be arranged, so the are located between two modules. For other infrastructure, a placement based on the requirements of the PV plant was not possible.

Figure 15: Lighting poles could be placed during planning phase so they are located between two PV modules and cause minimum shading.

Figure 16: Partial shading by railway infrastructure occurring on the west side during afternoon hours.

To evaluate the influence of these partial shadings, the minute values for shaded and non shaded strings during afternoon hours (all partial shading occurs on the railway side, in

Münsingen the west side) are investigated. First results suggest that the influence of the partial shading during a sunny day is not clearly visible, since all strings behave similar.

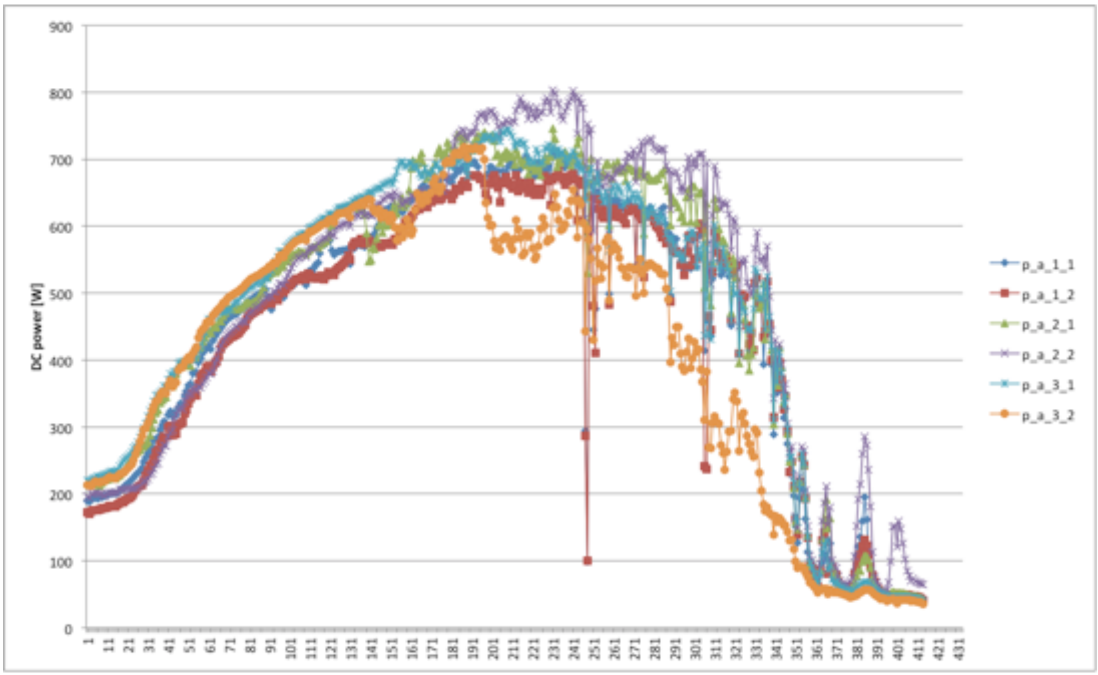

Figure 17: There is no clear indication of influence of the partial shading in DC power this day. Solar irradiation was slightly varying during second half of the afternoon leading to the unsteady results for DC output, but no string shows an obviously lower output.

During evaluation of other days, a more obvious influence of shading during afternoon hours was visible. This could be due to different points of time during the year for which the data is evaluated, since sun elevation and azimuth angles change and lead to different shading patterns but the obstacles stay the same. Unfortunately, a confirmation based on the high-resolved minute-based data in 2012 was not possible, due to construction work being carried out during the similar period of the year.

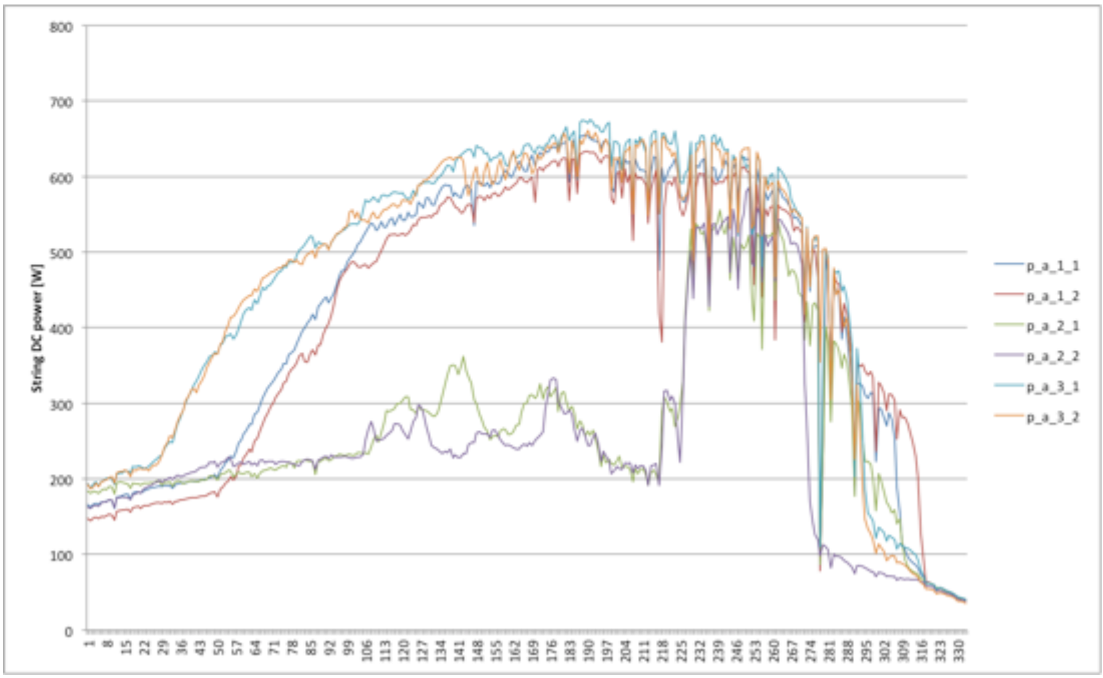

Figure 18: Two strings of the same array (p_a_2_1 and p_a_2_2) show influence of shading during a sunny afternoon later in the year. This could be due to different sun azimuth and elevation.

National and international collaborations

Space Energy Corporation, JPN

Space Energy Corporation from Japan delivered the bifacial solar cells for the project in Münsingen. Space Energy Corporation also made financial and know-how contributions to the measurement campaign and the interpretation of the data. A delegation has visited the innovative approach of bifacial noise barriers and was received by TNC Consulting AG.

Papers and press

The bifacial PV noise barrier plant and parts of the results from the measurement campaign have been made public to specialists at different conferences, including visual and oral presentations at the 24th Symposium Photovoltaische Solarenergie in Staffelstein 2009 or the bifacial PV workshop 2012 in Konstanz.

Together with the municipality of Münsingen, several articles have been written, varying from local information to specialized magazines.

Several visiting groups

National and international companies and institutes, including a delegation from South Korea railway authority, showed interest in the application of bifacial technology in noise barriers and have visited the PV plant in Münsingen. TNC Consulting has presented selected parts of the data from the measurement campaign during these occasions.

Maintenance

Operation of the worlds first bifacial PV noise barrier plant on a railway line led to some first conclusions after 4 years of operation.

- No performance decline due to proximity to railway line with additional deposition of dirt or iron dust could be proven by examining the measured data. Additional maintenance concerning necessary cleaning due to proximity to railway lines was unnecessary in the first 4 years of operation. Additional cleaning could become necessary in the future. Further data should be collected in the next years.
- Usual risk of vandalism for easy accessible PV plants applies to PV noise barriers as well.
- The use of glass-glass-modules allows for easier cleaning in the case of graffities.

Maintenance on noise barrier PV modules

Graffities in different size offered the unplanned possibility to examine their influence on production. Due to the fast reaction of the owner of the plant, the utility of Münsingen, only a short period of data is available. The incident took place in 2010, when only hourly-based values were measured, leading to a lower reliability of the evaluated set of data. Nonetheless, a reduction in performance down to 54%…60% during afternoon (graffities on the west side) can be shown.

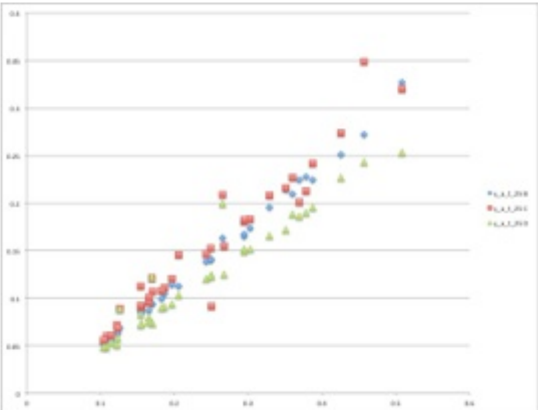

Figure 19: Yield of all groups during afternoon in spring 2010 with the grafitties. Due to the short period of time the grafitties were on the modules, the data is not so clear, but sufficient for an approximation of the yield.

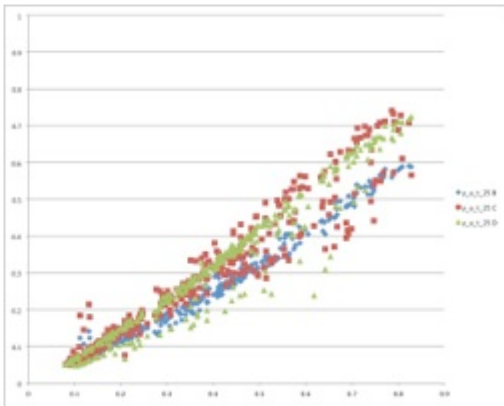

Figure 20: Yield of all groups during afternoon in summer 2010 without the grafitties. For comparison the best data sets (green and blue) have been used.

Although the bifacial PV modules are made of 2x10 mm glass and are therefore rather robust, two modules have already been destroyed during measurement period. Both times the modules showed small hit areas, from where the glass splintered. First signs of humidity entering through the cracks in the glass have showed up after short period of time. The first time the damaged PV module was replaced by a spare module prefabricated. The short time for replacement process proofed the modular concept of the bifacial PV noise barrier advantageous. The second damaged PV module (2012) has not yet been replaced, due to construction works and the fact, that there is no more spare module of this type available. A possible solution is worked on.

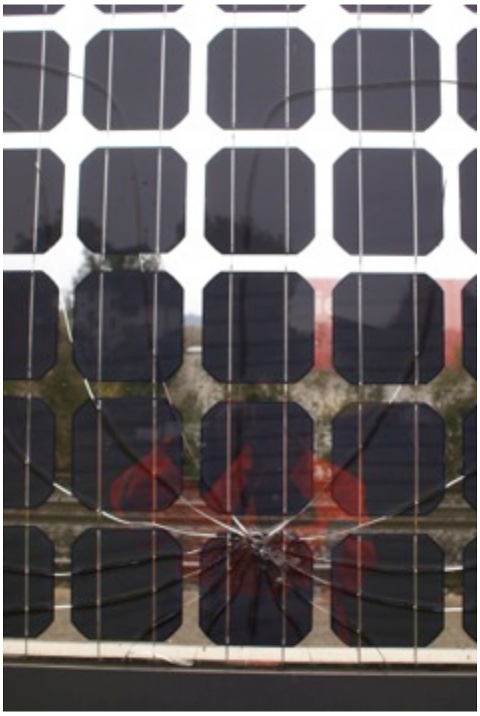

Figure 21 & 22: Willingly damaged PV module. The glass splintered from the center point of the hit area. Humidity entered through the cracks, leading to corrosion (dark stripe on the right side picture). The modules stayed electrically functional.

Maintenance in surrounding area

The maintenance of the plants along the railway-averted side of the bifacial PV noise barrier is in the responsibility of the landowner, in this case the community of Münsingen. Unfortunately the directly adjoining land in the east is not used and therefore not well tended. This leads to the growth of different plants that reach more than 1m heights above ground. These plants lead to a shadowing of the east side during the morning hours. Unfortunately, the exact time and place when this occurs cannot be specified without visual inspection.

Figure 23: maintenance of the railway-averted side (in the case of Münsingen the east side) is essential to avoid shading by wildly growing plants. The influence is not severe, due to the bifacial nature of the solar cells.

During the replacement of the PV module in 2011, the plants were cut down. Here the exact date of the maintenance is known, and it is therefore possible to compare production data from before and after the influence of the plants.

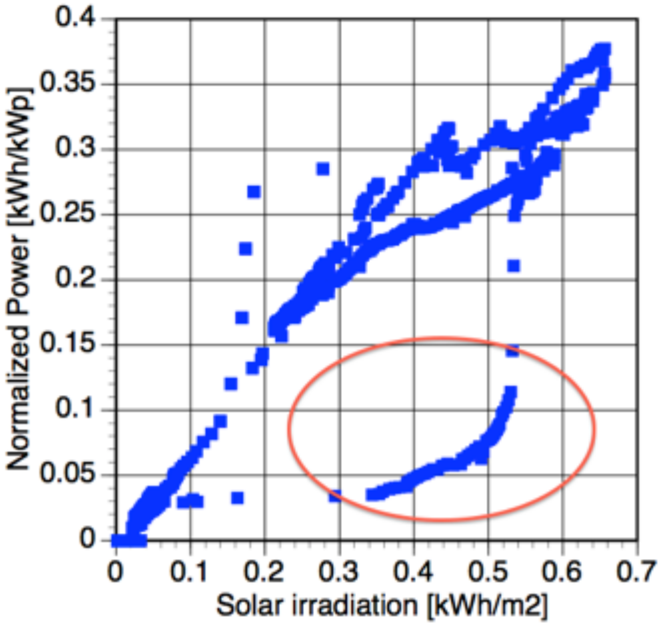

Figure 24: normalized power output before the cutting of the plants during morning hours. The measurement points in the lower right corner show the shadowing.

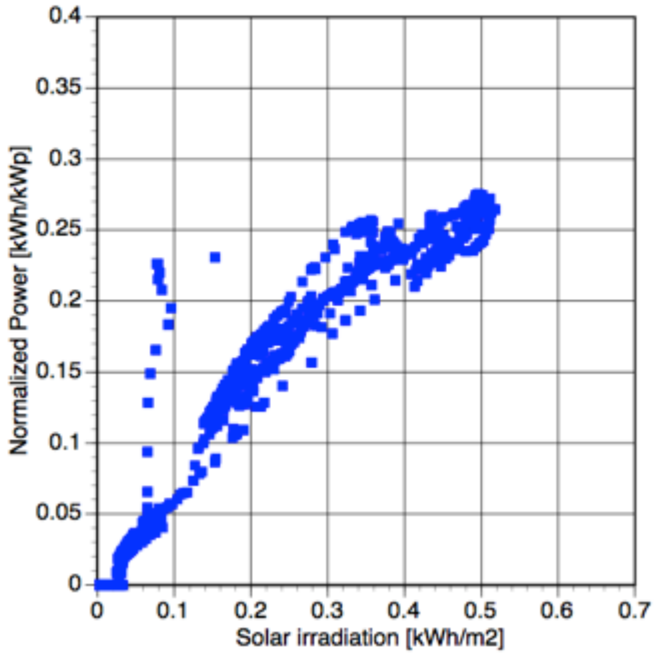

Figure 25: normalized power output after the cutting of the plants without the effects of shading. This increases the performance about +13% for the affected strings during morning hours.

Increase of the performance after cutting the plants of around 13% for the morning hours can be measured. Verification is only partially possible, since shading by plants cannot easily be reconstructed. The day of comparison after cutting the plants shows a little less solar irradiation during morning hours. For overall production, the influence is much smaller, due to bifacial properties of the PV plant.

Dropouts in production and data recording

Early in 2011 the AC energy measurement had a failure, leading to missing data. The equipment was replaced and has since worked well. In autumn 2011 the damaged PV module was exchanged. Almost one year later, the second PV module was damaged. The measured data have shown in both cases, that the PV modules were electrically still working. With humidity entering through the cracks in the glass and leading to corrosion on the cell surface and the bondings, it is only a question of time until the module will not work properly anymore. From the point of view of the measurement campaign, there is a small uncertainty in the influence of the damaged modules on the measured data.

In spring 2012 construction work on the new access to the train station area for bicycles was started. During this time, the noise barrier and therefore the PV modules were subject to additional shading caused by installations during construction work. For the most part of 2012 (until September) the construction work was going on. This makes the data acquired during summer 2012 unfit for comparison with preceding years.

Figure 26: Construction work for the direct bicycle access to the train station, which went on for the most part of 2012.

There have been short outages of communication to the data logger, leading in two cases to minimum loss of data.

Rating of success

The first years of operation of the bifacial PV noise barrier plant on a railway line in Münsingen show that the modular concept of bifacial PV noise barriers can be adapted to railway lines without drawbacks. The unavoidable partial shading by railway infrastructure such as power lines does not necessarily lead to large reductions in overall energy production due to the bifacial concept.

The measured data shows that the bifacial PV noise barrier plant in Münsingen works well. It was proven that the inverters work well with bifacial modules and two peaks a day. Sizing of the inverters and the electrical components is challenging for large-scale applications of bifacial PV noise barriers with differing front and backside efficiencies of the bifacial solar cells. The lower than originally calculated yield is mainly due to the shading of trees on the north end of the noise barrier, which is a site-specific issue and not an issue of the concept of bifacial PV noise barriers on railways.

Verification of influence of specific aspects of partial shading by railway infrastructure on energy production was unfortunately only partially possible, due to influence on the measured data by construction works outside of the PV plant. While during some days the influence of partial shading by railway infrastructure was visible in the measured data, this could not be verified for all days. These differences could be due to sun azimuth and elevation, which can only be verified in approximately the same period during the year.

With further minor adjustments in the plant layout based on the gained experience and developments in the technology of bifacial solar cells, the performance of future bifacial PV noise barrier plants can further be improved and probably almost reach the performance of a conventional south oriented PV plant.

Necessary maintenance was mainly caused by vandalism (graffiti and destroyed modules) and fast growing plants in direct environment of the PV modules. Soiling due to proximity of the bifacial PV plant to the railway track was no measurable issue during these first years.

The measurement concept of different module groups side by side for reasons of comparison has worked well for evaluating influence of specific shading effects on both sides of the modules and in different areas of the noise barrier. A less differentiated measurement equipment would not have been sufficient for separating the different influences on the bifacial PV plant in operating conditions.

The planned increase in time resolution of the measured data was implemented successfully and provided high resolved measurement data. This data helped verify and calculate effects such as the shading of trees on the north side more precisely. Other effects, such as influence of single plants or graffities could only be measured with the high time resolution of 1min values.

Outlook

Although there was a high interest in the concept of bifacial PV noise barriers on railways, it is still a niche application of PV. Besides different aspects of economics, some of which in the opinion of TNC Consulting could be mastered with large-scale installations, lacking experience in the operation of bifacial PV plants on railway lines is one of the reasons why no further projects have been realized so far. An ongoing measurement campaign could provide further data for operation of bifacial PV plants on railway lines. The advantages of a modular concept as applied in Münsingen has proven the advantages when exchanging damaged PV modules.

In the meanwhile, improved bifacial solar cells are available on the market. They promise higher overall efficiency (up to 20%) and a very well balanced front-to-back-ratio (bifaciality) of almost 100%. These solar cells allow an optimized plant design, increasing overall energy production of bifacial PV applications.

In the course of upcoming discussions on grid services and stability issues, a broad application of bifacial PV could help provide a more evenly distributed solar energy production. A further investigation on the beneficial effects of bifacial PV applications on solar energy production should be investigated in near future, focusing on questions such as technical and economical development and comparison to other forms of grid services.

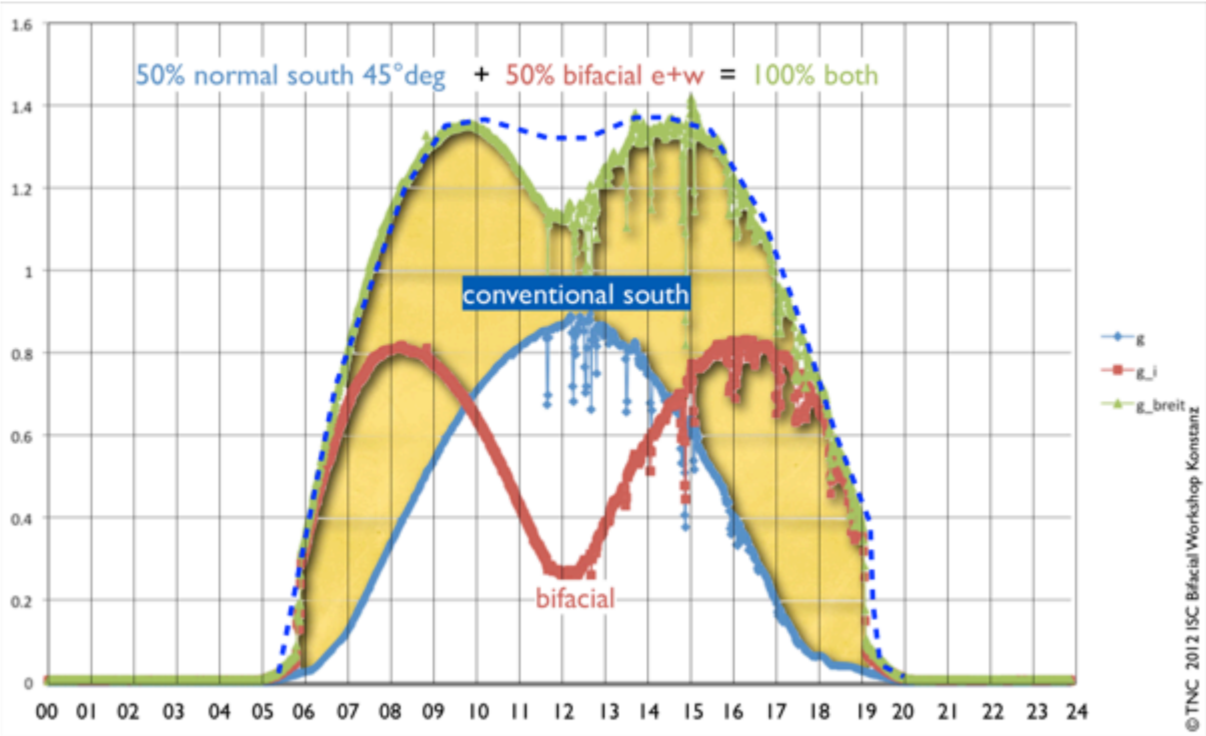

Figure 27: Possible contribution of bifacial PV applications to grid stability and more evenly distributed solar energy production based on the measured solar irradiation (where g is the solar irradiation for a south oriented and 45° inclined reference cell and g_i is the sum of solar irradiation in the east and west vertical plane in kWh/m2) in Münsingen.

References

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