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Influence of technological changes on the energy yield of PV modules: An outdoor study

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Abstract

To further increase the efficiency of PV modules, a variety of technical approaches targeting losses on cell and module level are pursued. Module efficiency is usually stated at standard test conditions (STC) whereas conditions during operation in the field are most of the time very different. From a customer perspective the specific energy yield is the far more important parameter, as it has immediate effect on the levelized costs of electricity(LCOE), which describes the costs of a kWh produced. The specific energy yield is strongly dependent on module characteristics at different operating points. Some of these properties such as low light characteristic, thermal behaviour or incident angle dependency can be influenced by technological changes resulting in a change of specific energy yield. To predict the quantitative effect of technological changes on annual energy production, module characteristics can be determined by outdoor measurements and fed into a simulation tool to quantify the gain or loss in annual energy yield of the changes applied. In this paper, two technological changes on cell and module level are investigated. First, the effect of anti-reflective coated glass is evaluated. The second investigation is related to a PERC cell structure. Therefore measured outdoor data from a photovoltaic test site are analysed to evaluate changes in module design with respect to their effect on outdoor performance. The results are compared to long term measurements of system installations to confirm the differences in energy yield. It is shown that technological changes can be applied on module and cell level that not only increase power under standard test conditions, but also lead to an additional improvement of the energy harvest per kWp and thus lower the LCOE.

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Keywords: Energy Yield; outdoor measurements; ARC; anti reflective coating; Q.ANTUM; local contacts; passivated rear; high efficiency; LCOE

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Nomenclature

I_{sc}	Short circuit current
V_{oc}	Open circuit voltage
P_{mpp}	Power at maximum power point
I_{mpp}	Current at maximum power point
ARC	Anti reflective coating
AoI	Angle of Incidence
IAM	Incident angle modifier
G	Irradiation
G_{isc}	Irradiation calculated from modules' I_{sc}

1. Introduction

In this paper, two specific technological changes on both module and cell level are discussed on the basis of short term module measurements over several hours and long term system data. The energy yield is strongly dependent on module characteristics at different operating points. Some of these properties such as low light characteristic, thermal behaviour or incident angle dependency can be influenced by technological changes resulting in a change of specific energy yield. The measurement and collection of the data has been performed at the Hanwha Q CELLS PV test site in Saxony-Anhalt, Germany[1]. First, the influence of front cover glass with anti-reflective coating (ARC) on the energy yield behaviour is investigated by analysis of single module measurements.

Second, as an example for technological changes on cell level, the Hanwha Q CELLS high efficiency Q.ANTUM technology is compared to a standard BSF cell technology. Modules with Q.ANTUM cells with dielectric passivated rear side and local contacts are analysed using short time single module measurements and compared to long term measurements of complete grid connected PV systems.

2. Experimental setup and data analysis

2.1. Hanwha Q CELLS photovoltaic test site

The experiments were performed at Hanwha Q CELLS' photovoltaic test site in Saxony-Anhalt, Germany, where data of photovoltaic modules and systems are measured with high precision and are stored into a database for further analysis.

Fig. 1. Modules and meteorological measurement equipment at the Hanwha Q CELLS test site in Saxony-Anhalt, Germany[1].

The Hanwha Q CELLS test site includes single module tests, system tests and sensor equipment for meteorological and optical measurements.

In the single module tests, the modules are mounted on free standing frames, facing south with adjustable inclination angle. Electrical data and the module temperature are monitored with a sample interval of 10 seconds. In addition to the measurement of voltage and current at maximum power point (MPP) operation, the IV-Curves of the modules are captured periodically, which allows to use the short circuit current I_{sc} and the open circuit voltage V_{oc} for analysis. Table 1 shows an overview of the quantities which are collected at the test site.

Table 1. Measured quantities at Hanwha Q CELLS test site[1].

Single module tests	System tests	Meteorological measurements
Vmpp[V]	Vdc[V]	Global irradiation[W/m²]:
Impp[A]	Idc[A]	• Horizontal
Voc[A]	Pac[W]	• Module plane
Isc[A]	Eac[kWh]	• Tracker plane
Tmod[°C]	Tmod[°C]	Direct normal irradiation[W/m²]
		Ambient temperature[°C]
		Wind speed[m/s] & direction[°]
		Relative humidity[%] & air pressure[hPa]
		Precipitation[mm]
		Solar spectrum

The single module tests also includes a two-axis solar tracker with a capacity of 6 modules, which allows to adjust defined angles between the propagation direction of solar irradiance and the surface normal of the test modules.

In the system tests, complete photovoltaic systems consisting of module strings and a grid connected inverter are monitored with a sample interval of 10 seconds. The module strings are permanently operated at MPP, and electrical data are measured on both DC and AC side of the inverter. The module temperature is measured by a PT1000 sensor, attached to the rear side of one module.

In addition to single module test and system test, the Hanwha Q CELLS test site monitors high quality meteorological and environmental parameters such as direct and global irradiance in different planes as well as the solar spectrum, ambient temperature, wind speed and direction, humidity, air pressure and rain amount.

For further details about the Hanwha Q CELLS photovoltaic test site and the parameters measured, refer to [1].

2.2. Data analyzing strategies

As outdoor measurements are influenced by a multitude of environmental factors as well as details of the measurement setup, derived quantities, especially those involving data measured on different devices show a broad scattering. An approach to reduce this scattering is self referencing [2], e.g. usage of the modules short circuit current as irradiation reference or calculation of the cell temperature from the open circuit voltage and the irradiation reference. Self referencing is used for analysis in this paper, e.g. to eliminate angular and thermal influences for the determination of the low light characteristic of a fixed ground mounted module on a clear day.

If a significant influence on the angular behaviour is expected, the dependency of the angle of incidence is determined using the two-axis solar tracker at clear sky conditions. For instance, this is the case for an evaluation of different front cover glasses. The determined characteristics are used as input for the commercially available software PVSYST [9], which calculates the expected energy yield and performance ratio for an arbitrary location. The predicted performance is compared to long term system data for validation.

3. Technological changes and influence on energy yield: Case studies

3.1. Front cover glass with anti-reflective coating (ARC)

Modules with anti-reflective coating on the front cover glass are available in the market from several manufacturers. With a refractive index between the indices of air and glass, ARC reduces the reflection losses on the air-glass interface at the front surface, leading to an improvement of module power under standard test conditions.

To evaluate the effect of the used AR-coated glass on the energy production potential, the dependency of the angle of incidence is determined for the investigated modules with and without ARC. The incident angle is defined as the angle between the module surface normal and the light propagation direction, which means that it is zero for perpendicular incidence. For the determination of the angle of incidence (AoI) dependency, modules with and without ARC are mounted on the two-axis solar tracker. On a clear day, the solar tracker is controlled in a manner that the incident angle varies between zero and 90 degree while electrical and temperature data are captured. The most appropriate quantity for this analysis is the short circuit current I_{sc}, as it is proportional to the light intensity reaching the active cell surface. The confirmation of the proportionality of I_{sc} and the irradiation for the used cell technology with back surface field (BSF) is presented in [6].

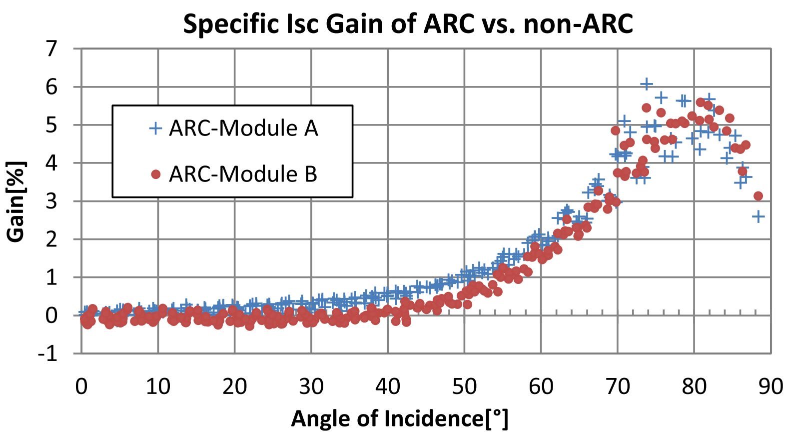

Fig. 2. Specific Isc gain of two ARC-modules with respect to average of two non-ARC-modules (zero). Both ARC-modules show a rising gain for increasing incident angles larger 45° with a maximum of approximately 5% at an incident angle of 80°.

In Figure 2 the gain in specific Isc, which in this case is defined as the short circuit current normalized by its STC value from outdoor measurements, of two modules with ARC-glass compared to an average of two non-ARC modules over incident angle is presented. It can be observed that the gain increases with higher angles with significant differences for angles larger 45° to a maximum of approximately 5% at an angle of 80°. Thus, the increased energy output at STC not only fully translate into an equivalent gain in energy yield, there also is an additional energy yield gain, which means extra kWh/kWp for oblique angles of incidence. The magnitude of the additional energy gain is dependent on the distribution of energy conversion over incident angle, which varies with location, weather and orientation.

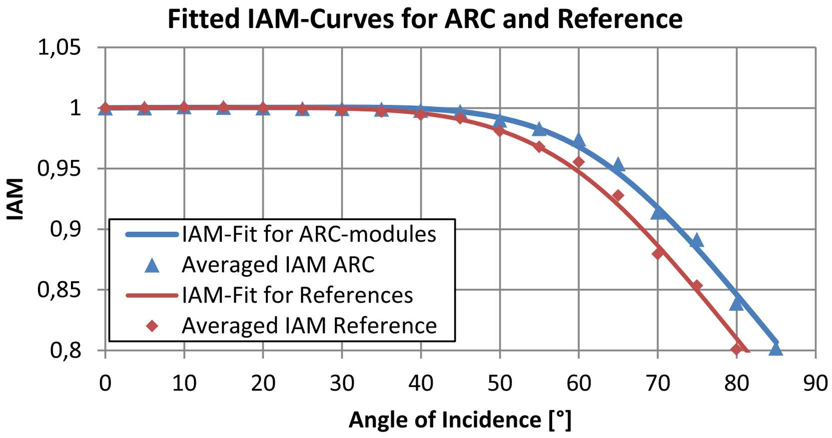

Fig. 3. The line plots are fitted IAM-curves as input for the energy yield simulation. The symbols show IAM value averages of two modules and over 5°.

In the commercially available simulation software PVSYST [9], the dependency on the angle of incidence can be considered by redefinition of the incidence angle modifier (IAM). The IAM describes the fraction of irradiation reaching the cell surface as a function of the angle of incidence and with respect to normal incidence [5] using the experimental determined angle dependency. Figure 3 shows the fitted IAM curves for ARC-modules and reference modules.

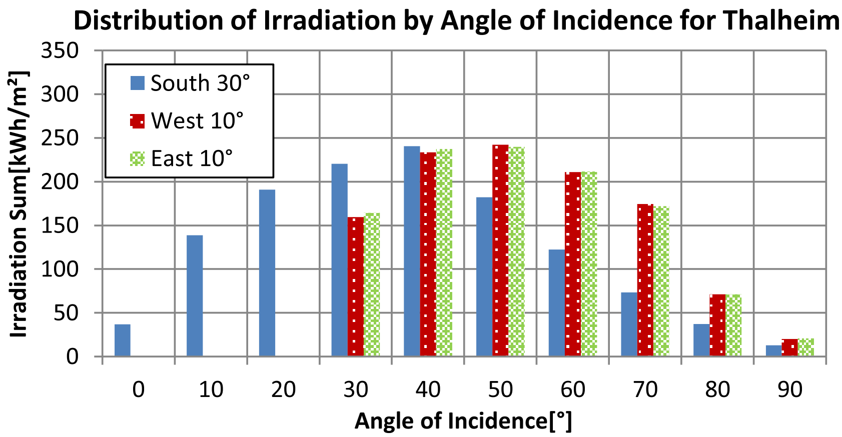

Fig. 4. Distribution of global irradiance for different system orientations and inclination angles by the angle of incidence. The presented values are calculated using the angle of incidence [4] and global and direct irradiation measurements. The diffuse component is assumed as isotropic.

Figure 4 exemplarily shows the distribution of the global irradiation for different orientations and inclinations by the angle of incidence for the location Thalheim, Germany. Since the irradiation is not directly measured for each orientation, the irradiation values for east and west orientation at an inclination of 10° are derived from measured quantities under the assumption of an isotropic diffuse irradiation component.

A simulation for Berlin, Germany for a south-facing installation with optimal inclination estimates a specific energy yield gain of 1% compared to standard modules without ARC.

For a flat roof installation with module strings facing east and west, the estimated annual gain rises due to the shift of the distribution of irradiation toward more oblique angles of incidence (see Figure 4). Hanwha Q CELLS offers the flat roof solution Q.FLAT-G3 [8], where modules are mounted facing east and west with an inclination angle of 10° (see Figure 5).

Fig. 5. The Hanwha Q CELLS flat roof solution Q.FLAT-G3 increases the roof space utilization to up to 82% - twice as much as an installation with 30° inclination. The modules are facing east and west with an inclination angle of 10° [8].

The energy yield simulation for a Q.FLAT-G3 system in Berlin estimates an annual specific energy yield gain for ARC modules compared to non-ARC modules of approximately 1.5%.

3.2. Hanwha Q CELLS Q.ANTUM cell technology

Another property having large influence on the energy yield is the low light performance. In this section we compare the Hanwha Q CELLS Q.ANTUM cell technology to standard cells with an Al-BSF. The Q.ANTUM cell technology was developed by Hanwha Q CELLS to reduce recombination losses by replacement of the Al-BSF on multi crystalline p-type-cells by a dielectric passivated rear with local point contacts.

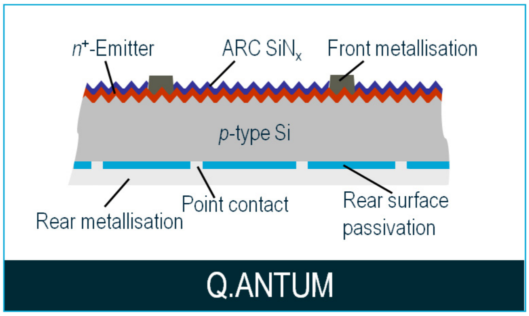

Fig. 6. Schematic cross section of a Q.ANTUM cell [6]. The Al-BSF at the rear side of a standard Al-BSF cell is replaced by a rear surface passivation layer with local point contacts.

Figure 6 shows the schematic cross section of a Q.ANTUM cell [6]. Under standard test conditions, the realized power gain is in the range of 3-4% rel. Since the full area rear contact of an Al-BSF cell is substituted by local point contacts, the series resistance Rs of the Q.ANTUM cells is higher compared to the Rs of a standard Al-BSF cell. Because of the quadratic dependence of the ohmic power losses on the current, the elevated Rs results in an improvement of the relative low light behavior, which is defined as the efficiency at a given irradiance normalized to the efficiency at an irradiance of 1000 W/m². Further informations on the high efficiency Q.ANTUM cell technology are available in [6] and [7].

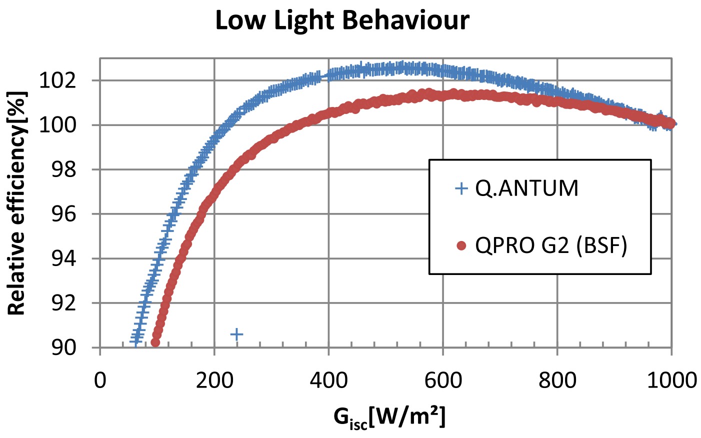

Fig. 7. Low light behavior of a module with Q.ANTUM cells (blue circles) and a module with Al-BSF cells(red dots). A significant improvement in low light behavior can be observed for all irradiations below 1000W/m². For an irradiation of 200 W/m², a difference of 2.5% can be observed.

Figure 7 presents the low light behaviour of a module with Q.ANTUM cells with passivated rear contact (blue) and a Q.PRO-G2 module with Al-BSF cells (red), determined outdoor on a clear day in July. The individual measurements are temperature corrected on base of V_{oc} and each modules' I_{sc} is used as irradiation reference. The stability of the passivation and the linear dependency of I_{sc} and G under low injection conditions has been proved and presented in [6]. A significant improvement in low light behaviour of 2.5% compared to the value of BSF modules at an irradiation of 200 W/m² can be observed for the investigated modules. Feeding this information into the energy yield simulation model, an annual energy yield gain in the order of 1.5% is expected for the location of the test site(Thalheim, Germany) in addition to the STC gain.

In the system test, a PV system containing modules of the Q.ANTUM cell technology is compared to a system with Q.PRO-G2 (BSF) modules. Both systems have been installed in October 2012 and consist of a grid connected SMA SB 2500 inverter and a module string of 10 modules with total peak powers of 2.5kWh for the Q.ANTUM system and 2.44kWh for the BSF system. In the analysis the indoor flasher measured peak power is used for calculation of the specific energy yield.

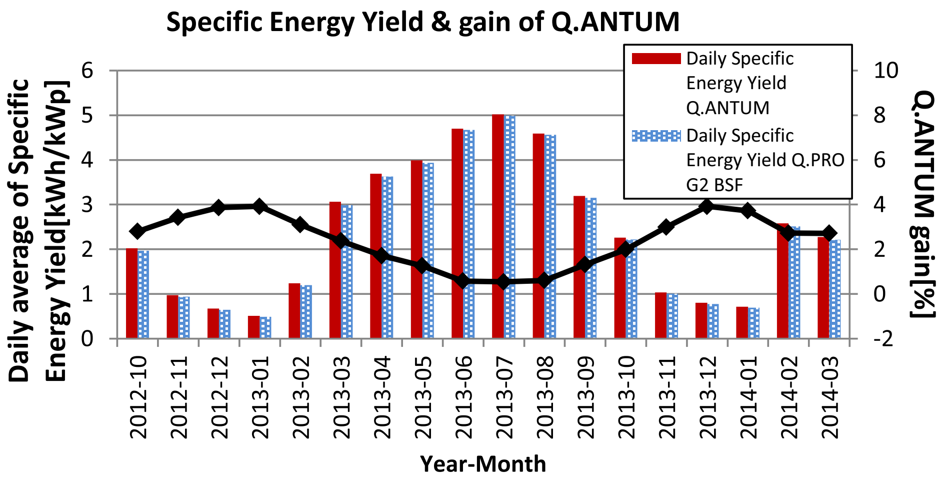

Fig. 8. Measured Specific Energy Yield gain of Q.ANTUM compared to Q.PRO-G2 (BSF). The Q.ANTUM system shows a gain of at least 0.5% and rises to up to 4% in the winter months.

In Figure 8, the monthly values of specific energy yield are presented as bar plot and the relative gain of Q.ANTUM compared to Q.PRO-G2 (BSF) is depicted as line plot. To limit the effect of tolerances in inverter efficiencies, DC quantities are used for this evaluation. Resolving differences in the range of few percent from outdoor measured data requires careful analysis of the validity of every single data point. Effects such as partial shading, snow conditions, measuring equipment downtimes etc. can strongly influence the analysis and need to be removed using several data filters. Since effects of shading or snow covering mostly occurred at conditions of low irradiation, at which Q.ANTUM takes advantage of its superior low light behavior, the filtering tends to result in an underestimation of the Q.ANTUM gain. Hence, the gain curve in Figure 8 is a lower bound of the real energy gain.

The characteristic correlation of irradiation conditions to the relative gain of Q.ANTUM can be observed by comparing the relative gain to the specific energy yield plots in Figure 6. In the summer months, the irradiation and thus the specific energy production of both systems is on a relatively high level. The Q.ANTUM system shows a slight gain of at least 0.5%. In the winter month the measured Q.ANTUM gain significantly rises to up to 4% due to the superior low light behavior. In the sum over the first year of operation, an energy yield gain of 1.6% per installed kWp compared to the BSF system is observed. This is an excellent agreement with the predicted value of 1.5% from the simulation presented above.

4. Conclusion

It was shown that the usage of ARC front cover glass not only fully translates the higher STC power into energy production, but also results in an additional, location- and orientation-dependent gain in specific energy yield in the range of 1% to 1.5% per year for the considered cases. ARC front cover glass is used in all module products currently available from Hanwha Q CELLS.

With the high efficiency Q.ANTUM cell technology, the increase of peak power under standard test conditions is accompanied by a superior low light performance. A simulation on the base of short time outdoor data estimated a gain for Q.ANTUM of 1.5% compared to BSF. To confirm simulation results by real outdoor measured data, long term system data were analysed and compared to the simulation results. Resulting in an additional energy yield gain of 1.6%, the long term experiment shows good agreement with the simulation results.

As presented in this paper, technological changes can be applied to photovoltaic modules which not only increase module peak power, but also improve the energy yield per kWp respectively the performance ratio of a photovoltaic installation and thus lower the LCOE. Improvements in the energy yield translate immediate on the levelized costs of electricity (LCOE).

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