SUNTHINK – DEVELOPMENT OF A NOVEL SOLAR ACTIVE SUNSHADING SYSTEM WITH THIN FILM PV CELLS

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ABSTRACT: SunThink is a novel photovoltaic system, integrating thin film solar cells in conventional sunscreen louvers (Venetian blinds). Multifunctional use of PV system and sun screen makes façade integrated PV economically feasible as an installation system and a one axis-tracking are already implemented, additionally increasing solar energy yield. Compared to conventional façade integrated PV, more than 50 % solar energy surplus can be expected. Two south-oriented prototypes were built up in order to study energetic and thermal operation data. The energetic yield strongly is limited to the self-shading behavior of the horizontal louvers. As major research topics of the study, thermal behavior, the economically optimal PV area on each louver as well as the optimal tracking strategy will be discussed. Measurement data were used to validate a simulation model based on the platform INSEL.
Keywords: Façade, Thin Film, Tracking

1 INTRODUCTION

The idea of SunThink Solar Active Shading Systems is to simply combine flexible thin film photovoltaics (PV) with conventional sunscreen systems, especially Venetian blinds. With these blinds, consisting of single, moveable and horizontal louvers, SunThink merges solar active use with sun protection. In order to cover these functions, flexible thin film PV are bond to the curved profile of conventional louvers. Figure 1 shows the operation principle of SunThink generators.

Multifunctional use of PV and Venetian blinds brings several advantages: first of all, sunscreen is used at high solar irradiation and due to this fact, new areas become applicable for Building integrated PV.

Office and administration buildings have strict specifications for sun and glare protection creating a high potential for substantial cost reduction: assembly devices for PV modules and even a one-axis tracking system are already included in the sunscreen, which has to be provided to buildings anyway. Furthermore, this one axis tracking helps to increase solar energy yield.

Building integrated PV (BiPV), as one of the fastest growing markets, discovers the façade as having high potentials for solar energy use. According to [1], the potential of fixed, façade integrated PV in Germany is nearly 30 GWp, which could be enhanced to roughly 45 GWp with one-axis tracking. Compared to roofs with a potential of up to 129 GWp [1], this could significantly contribute to BiPV and thus be an incentive for bringing thin film PV onto the market.

However, especially at high sun angles, the problem of vertical shading between the louvers is becoming immanent. In the upper area of each louver, beam radiation is significantly dropping and only diffuse radiation can be used. The self-shading behavior and economically optimal PV equipment rate is one of the major research topics in the present study.

Façade integrated PV actually is represented by fixed and tracked systems. Fixed systems could be installed vertically or optimally point south with a 30° module angle (latitude: 48°N). Examples for tracked systems with crystalline cells are produced by COLT International AG [2], ADO Solar [3] and Schüco [4], the later ones promoting large sized horizontal one-axis tracked systems. A noteworthy example for multiple use of BiPV is Nikolaus-Fiebiger-Zentrum [5] in Erlangen, Germany. Paul-Löbe-Haus [6] in Berlin can be mentioned for special tracked roof systems. The innovative approach of SunThink is a multifunctional use of standard Venetian Blinds with thin-film PV.

Thin-film cells generally are less sensible against high cell temperatures and low, diffuse irradiation. Concerning the self-shading problem and the expected overheating behavior of SunThink generators, thin-film PV cells are particularly suitable to the present application.

2 EXPERIMENTAL STUDIES

2.1 Set-Up of the Prototype

The SunThink project started at the beginning of 2005 with the realization of two functional prototypes. The test rigs were built up at the Solar Research Center of Technische Universität München.

Due to a necessary weather protection, both prototypes were installed in an already existing double skin façade test stand. Double skin façades consist of a secondary glass façade in front of the original building,

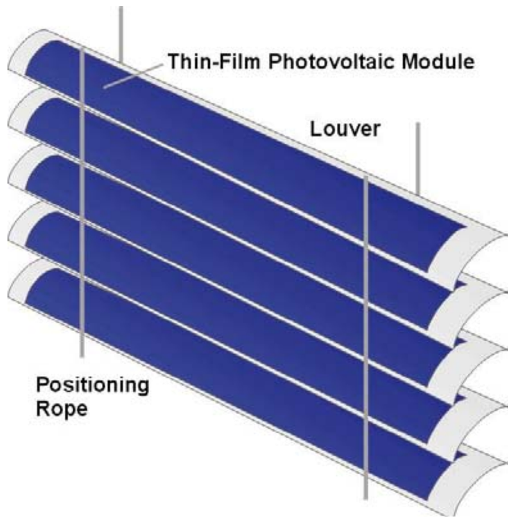

Figure 1: Functional Design of SunThink

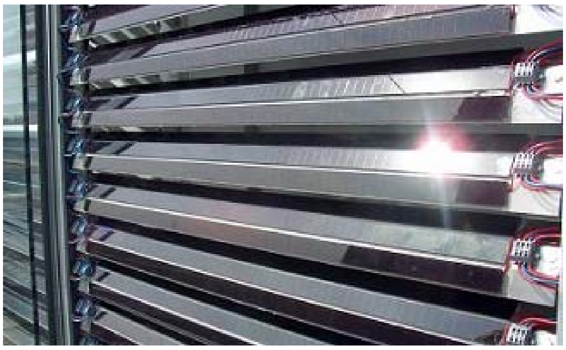

Figure 2: Prototype Design of SunThink

thus establishing a thermal buffer zone. Because of being installed in a glass enclosure working as a greenhouse and due to the high absorptivity of PV cells, the prototypes show a strong heating behavior.

Figure 2 shows a photo of the SunThink prototypes. As can be seen, the louver area is equipped with three single PV modules, making it possible to measure power output of different louver segments, especially the shaded part.

In 2005, the thin-film PV market was dominated by inflexible copper-indium-sulphide (CIS) and amorphous silicon (a-Si) cells deposited on glass. For that reason, the present SunThink models were realized with inflexible a-Si cells from SCHOTT Solar GmbH, who could provide suitable module dimensions. As can be seen in fig. 3, each louver is equipped with three modules. 20° offset angles approximate the curved profile of conventional louvers. Fig. 3 and 5 show views of one louver and display the three planar areas equipped with SCHOTT ASI 3 0o 57/894/025 [7] modules.

One test rig is built up of 16 louvers with three strings each. The louver length is 1100 mm and the width is 80 mm, a standard for Venetian blinds. The PV module length is shorter than the louver, so that electrical connections could be installed on both sides.

The top modules of each louver are connected in parallel as are center and lower modules, respectively. Top, center and lower modules thus form one *string* each. So, detailed measurements on each louver segment are possible. Taking shading into account, this allows studies on the economically optimal PV area.

The maximum power of one module at standard test conditions (STC) is P_{max} = 1.04 W [7]. 48 modules build one prototype and could generate nearly 50 W, but different elevation angles of the three louver modules and self-shading on the top modules decrease the energy yield. Each module consists of 57 cells in series. Due to pure series connection, the modules have a high open-circuit and MPP voltage level at low module currents. For that reason, it is difficult to find compatible DC/AC inverter systems.

If individual user operation of each façade axis is desired, every SunThink generator should be connected to a single inverter system. In order to handle multiple power outputs, small module inverters or a 2-stage

Figure 3: Louver Design of SunThink

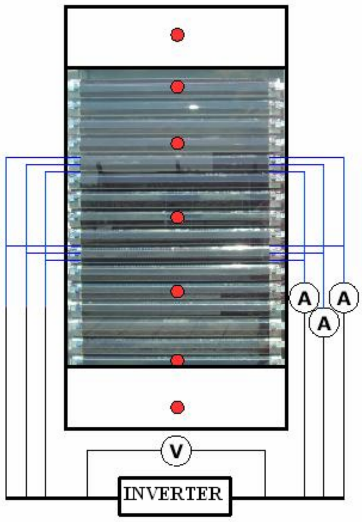

Figure 4: Functional Measurement Structure

inverter concept is required. The two stage system is equipped with a local DC/DC conversion and maximum power point (MPP) tracking combined with central DC/AC inverters. In order to guarantee a sensible interaction with the user, monitoring devices should be provided.

2.2 Data Acquisition

The electrical power yield is the main focus of the present studies. Thermal behavior is a very interesting and important by-product of the investigations.

PV cells are sensible to the cell temperature. The used ASI-Modules have a temperature coefficient of only 0.2 %/K compared to crystalline 0.5 %/K [7]. Figure 4 shows the location of electrical current, voltage and temperature sensors. Red dots indicate the temperature sensors. Vertically fluctuating temperature profiles bring the problem of different MPPs in each module. Connected in parallel, DC/AC inverters could adjust to indefinite MPP values at limited efficiency.

As is indicated with blue lines in figure 4, louvers are connected in parallel and thus form three strings. Sixteen louvers build one prototype with 48 modules in the top, center and lower string, respectively.

Because of parallel connection to one inverter, current measurements show differences between the strings at equal voltage. Self-shading behavior can easily be monitored with this measurement set-up.

Temperature as well as current and voltage data are collected with Vaisala QLI Sensor Collectors and monitored with LabView. Solar irradiation is measured with a pyranometer installed in the vertical façade level allowing a direct comparison of module characteristics at all positions and louver angles.

2.3 Tracking Strategies

Figure 5 shows the side view of a louver. Three planar louver thirds are bent at 20° offset angle and thus approximate the curved profile of standard Venetian Blind louvers.

Figure 5 also shows two essentially different tracking strategies. “Standard Tracking” aligns the center module, whereas “Cut-Off Tracking” points the lower module

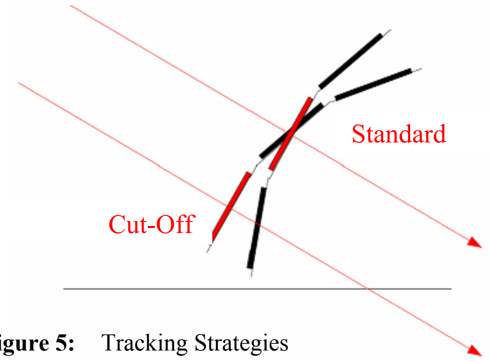

Figure 5: Tracking Strategies

directly to the sun. Both strategies are designed to ensure glare protection, which means to totally screen beam radiation from the building.

Even more than Standard Tracking, the Cut-Off strategy shades the top modules for a long time period every day, because the louver is tracked at higher elevation angles.

2.4 Characteristic Efficiency Curves

Characteristic efficiency curves of each string (upper, center and lower modules) and a performance comparison as a function of solar irradiation are given in figure 6. The data are acquired on a sunny winter day (s = 700 W/m², T_∞= 5°C) with the Standard Tracking strategy. The red line depicts efficiency of the optimally aligned center string.

Theoretical (STC) efficiency of one Schott ASI module is nearly 6.5 % [7]. Maximum efficiency means optimal adjustment, low cell temperature and absolutely no shading. Real measurements have to take account for self-shading and a remarkable vertical temperature profile (see section 2.5) deviating from STC temperatures (T_{STC} = 25°C).

As can be seen in fig. 6, the measured efficiencies range to STC values on a cold, sunny winter day. Thin-film PV cell properties at low radiation cause the so-called "efficiency knee". Thin-film cells show a lower dependence on low, diffuse radiation than crystalline cells. Due to this behavior, efficiency as a ratio of electrical power and solar irradiation is increasing at lower irradiation levels. Characteristics of the efficiency knee depend on ambient or cell temperatures, respectively: cold winter days show a steeper, warm summer days a more shallow knee.

Strategy of Standard Tracking points the center module directly to the sun bringing the highest efficiencies for the center string. The green characteristic curve indicates the lower modules showing lower efficiency because of a 20° deviation from direct sun angle. The blue curve depicts the upper modules showing self-shading behavior. Due to this, energy yield of the upper modules is limited and their efficiency has a negative gradient at high irradiation.

Global irradiation increases during noon, but tracking increases shading. Due to the different sun angles, this applies basically to noon time in winter and to nearly the complete day in summer.

The relatively small differences shown in figure 6 can also be explained with wintry low sun angles. In Munich (48°N), sun angles during winter time are only reaching 18.5°. Therefore, a bigger part of the upper modules is exposed to beam radiation, whereas in summer, shading would get more significant.

2.5 Vertical Temperature Profiles

Double skin façades work similar to solar air collectors with the sunscreen system as a thermal absorber. Free convection occurs due to buoyancy effects in the façade box both cooling the PV modules and preheating air, which can be used for domestic applications. However, overheating of the PV modules as well as a strong vertical temperature gradient have to be expected.

Air temperatures are measured at both in- and outlet of the façade (see fig. 4). Louver temperatures are collected at the top and bottom louver as well as at three louvers between. Fig. 7 shows the results for a clear, sunny winter day (s = 700 W/m², T_∞ = 5°C), where the blue curve depicts ambient temperature.

Light green indicates the inlet and dark green the outlet temperature curves. Red, orange and yellow curves show the louver temperatures.

The top louver reaches a temperature rise of nearly 35 K compared to 5°C ambient temperature. Air temperature lift between in- and outlet is nearly 10 K and between outlet and ambient temperature 15 K. The difference between ambient and inlet temperature is due to a strong thermal boundary layer at the secondary façade. If SunThink is combined with double skin façades, it could work as an air collector and would be able to preheat ambient air to room temperature, thus reducing wintry heating loads.

Accounting for summery heat protection, i.e. reduction of cooling loads in the building, a considerably warm sunscreen system near the façade could negatively

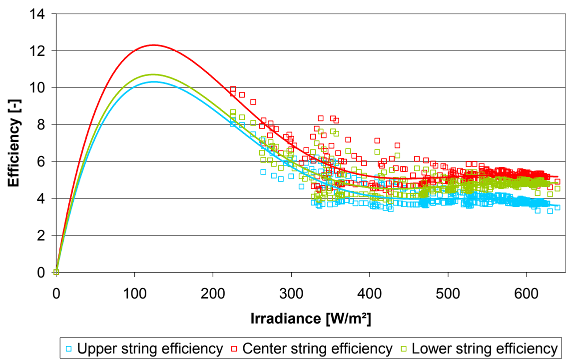

Figure 6: Characteristic Efficiency Curves of Lower, Center and Upper Strings

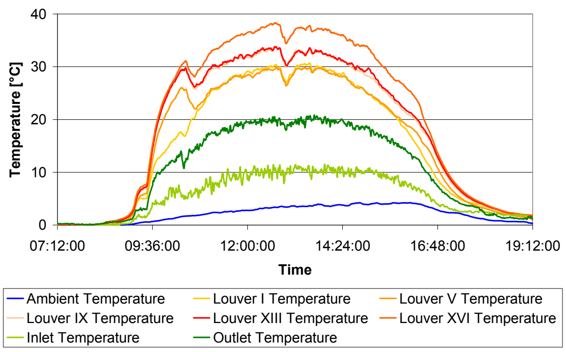

Figure 7: Vertical Temperature Profile

influence the building's overall energy consumption. This aspect has to be studied in further investigations.

3 THEORETICAL STUDIES

3.1 The Simulation Platform INSEL

After a thorough study of numerous dynamic simulation programs for solar systems, INSEL turned out to be a suitable platform for modeling SunThink.

INSEL is an acronym for **IN**tegrated **S**imulation **E**nvironment **L**anguage. It provides an integrated environment and a graphic programming language for the creation of simulation applications. The basic idea of INSEL is to connect blocks to block diagrams that express a solution for certain simulation tasks [8]. INSEL includes components of solar electrical and thermal plants and blocks to simulate complete renewable energy systems. In the present study, the test reference year (TRY) of Munich (48°N, 11°E) is used as a database for the simulations.

3.2 Set-Up of the Simulation Model

The photovoltaic block (PVI), figure 8, is based on the classic two-diode model. Due to smaller filling factors of a-Si, application of the two-diode model doesn't yield absolutely exact simulation results. The filled squares in fig. 9 depict simulation results of a sunny winter day (s = 700 W/m², T_∞ = 5°C).

Green squares show values of the lower module and red squares represent the center module, pointing directly to the sun (Standard Tracking). At low irradiation values in the afternoon, simulated curves show a 2-5 % deviation compared to measured data.

Anyway, this small deviation can be tolerated for calculations of energy yield and economic aspects. With the obtained results, an experimentally validated extension to yearly simulation could be realized.

3.3 Tracking Strategies

Beside an optimal energy yield, also glare protection and partial optical transparency are important specifications for advanced tracking strategies. In section 2.3, two strategies were defined: Standard Tracking and CutOff-Tracking.

Detailed analyses of both tracking strategies are illustrated in figure 9 with an additional focus on the upper strings. Here, cumulated monthly irradiation values are shown. For a better comparability of different tracking strategies and strings, the cumulated solar energy on a

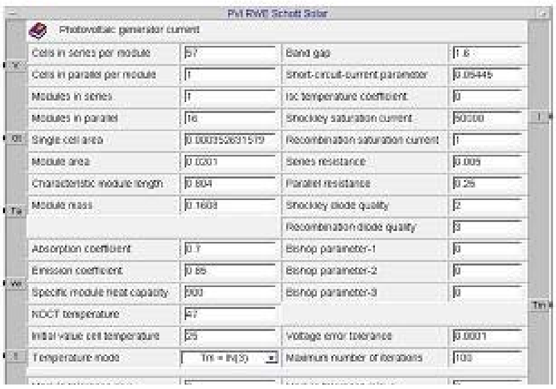

Figure 8: Photovoltaic block PVI with two-diode model parameter of SCHOTT ASI modules

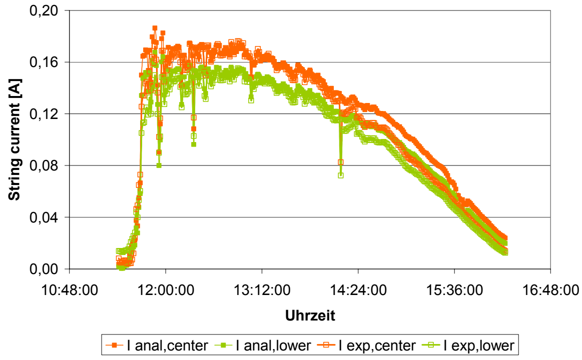

Figure 9: Validation of the Simulation Model

horizontal surface is given as a reference (TRY) for the location of Munich, Germany. This reference is displayed as orange line in figure 10.

The green curve shows solar irradiation on a vertical façade pointing to south. In the summer case, there is a significant difference between horizontal and vertical surface, because of the maximum sun angle rising to 65°.

For a better understanding of figure 10, the yearly surplus (= increment) of solar irradiation is given in figure 11 with a horizontal surface as reference. The green column again shows reduction of solar energy yield compared to horizontal surfaces, which amounts ~ 35 %. It can be generally said, that these systems are not able to work economically.

Blue curves depict yields of the upper strings in fig. 10, blue columns the yield reduction in fig. 11. Losses due to shading amount 45 % for Standard and 80 % for Cut-Off Tracking. It can be said, that the upper string is not able to operate economically for both tracking strategies, even with slight advantages for the Standard Tracking. Significant reductions of solar energy yield during summertime have to be explained with maximum louver and sun angles creating strong shading behavior.

The center string, shown by the yellow curve in fig. 10 and yellow column in fig. 11, shows a significant energy increase when implementing one axis Standard Tracking. One axis tracking nearly has twice the energy yield of vertically fixed, south oriented PV.

As an optimal elevation for the location of Munich, 30° module angle pointing to south has to be considered and is given in the red curve and column. SunThink systems with their already implemented one-axis tracking (yellow) are nearly able to reach values for optimal elevations (red) and

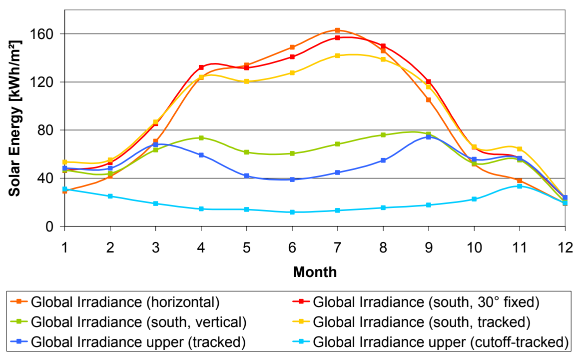

Figure 10: Monthly Solar Energy Yield

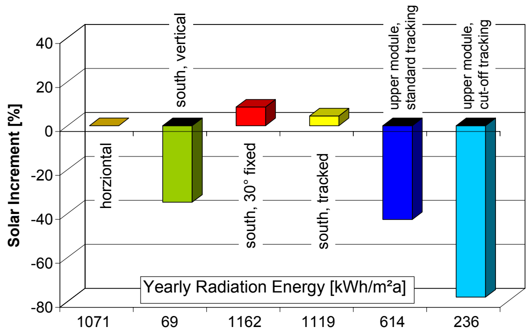

Figure 11: Solar Energy for Various Orientations

are therefore able to work economically.

3.4 Economically Optimal PV Area

As was shown in the previous sections, Standard Tracking is more insensible to shading as the Cut-Off strategy. Thus, economical calculations were only performed for Standard Tracking.

Figure 12 shows a bar chart, which refers to the left coordinate and a line chart, which refers to the right coordinate. The bar chart shows cumulated solar energy yield of the different modules. The line chart gives cumulated electrical energy yields with dots depicting the exact values. As a reference, the optimal PV configuration (30° module angle, south) is shown as green bar with yellow dots. The blue bars and the yellow curves are corresponding to upper, center and lower strings of the SunThink prototypes.

Horizontal lines show the minimum energy yield in kWh/kWp for given annual rates of return and give boundaries for cost-effective use of PV applications. The red line stands for 0 % return rate, the green line for moderate 2.5 %.

In a first estimation, comparison to standard PV applications is possible with calculating conservative 5 €/Wp for the SunThink system [9]. Anyway, due to multifunctional use and the application of thin-film PV, a high cost reduction potential is predicted. The annuity calculation is based on a credit by the German bank Kreditanstalt für Wiederaufbau (KfW) [10]. The KfW-credit provides 3.4 % interest, 10 years duration and is 2 years free of redemption. It was created as incentive for PV installations in Germany. The income is based on the German law EEG, where, in 2006, electrical energy from façade integrated PV additionally is subsidized with 0,568 €/kWh.

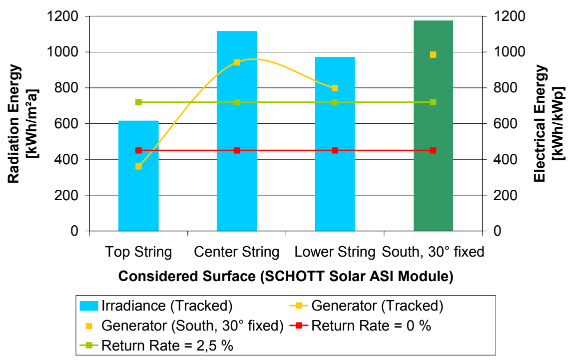

Figure 12: Energetic and Economical Results

As can be seen in fig. 11, the optimally tracked center module of SunThink is cost-effective like standard generators. The lower module just reaches profitability, whereas the upper module mostly is shaded and does therefore not work cost-effectively. It can be concluded that the lower 2/3 of the total louver are an optimal PV equipment area. Furthermore, it can be stated, that for the first time, SunThink reaches economic operation in façade integrated systems.

4 CONSIDERATIONS ON SHADING PROBLEMS AT DIFFERENT CONNECTION STRATEGIES

The very special design of louvers for Venetian Blinds isn't corresponding to the typical surface shape of photovoltaic applications. Small width and big length reduce the possibilities of electrical cell connection. Conventional modules are built up by connection in series and in parallel. Due to an adaptation in cell connections, the module voltage and current are able to match inverter characteristics. Shading of single cells only is severe, when single cells connected in series are totally shaded perpendicularly to the main direction of electrical current.

The used Schott ASI modules are built up of 57 single cells connected in series. Pasted to the louvers, the series connection is horizontally and self-shading occurs only in the upper parts of the cells. Higher sun or module angles reduce the irradiated cell area, but do not shade one of the cells connected in series completely.

Figure 13 shows different cell connections for SunThink applications. The red arrows display the direction of series connection or direction of current flow respectively. On the left side, four long cells build up the module ("Cross Striped"). This module is characterized with high current and low voltage bringing additional advantages in handling the system. The right side shows a higher number of smaller cells ("Short Striped") creating high voltage and low current.

Both cell connections have critical cases for shading. For the cross striped connection the critical shade comes directly from tracking, i.e. the upper louver. Critical shade for short striped connections could come from positioning ropes or sunscreen respectively window frames.

Standard inverters aren't fitting modules with pure series connection and small power generation. Module inverters could deal with small power generation and individual shading. Large façade areas with a large number of single SunThink generators should have one inverter for each generator. Due to a variable, user determined adjustment, every blind could thus be adjusted to optimal power yield individually.

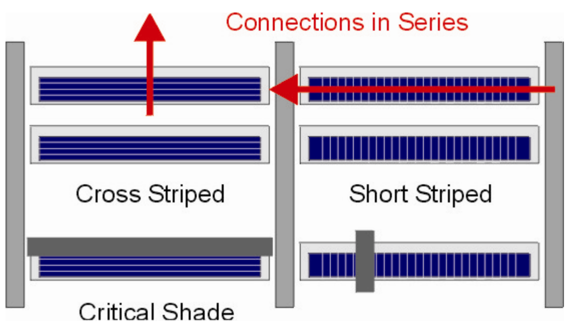

Figure 13: Connection in seires with critical shade

5 CONCLUSIONS

5.1 Technical Feasibility

Due to the temporary unavailability of flexible thin-film PV modules, Schott ASI Modules deposited on glass had to be used for the present studies. New developments on the thin-film market may have the potential to realize SunThink with flexible PV cells. DC/AC inverter problems could be handled with small module inverters or with a 2-stage inverter system.

Electric wires could be used as positioning ropes or be installed separately. The wires have to be weather and UV compatible and should be durable for typical warranty times of PV cells, i.e. 20 years. Every SunThink generator must have a user control unit but should generally be controlled by central building control systems. Users could be encouraged to sensible use of SunThink generators with an interactive display of energy yields.

5.2 Electric Energy Yield

Two SunThink prototypes were installed in the south oriented test façades of the Solar Research Center at TU München. Comparison between fixed PV pointing to south under 30° and one-axis tracked, façade integrated SunThink systems gives the following results:

- Façade integrated, horizontally tracked systems increase solar energy yield up to the level of optimally inclined PV generators.
- Tracking in the winter case increases the yield compared to a horizontal surface.
- SunThink operates economically.
- The upper third of the louvers is shaded over a long period of the year. Therefore, economical use isn't possible and an optimal PV equipment area would be the lower 2/3 of the total louver area.

5.3 Future Investigations

The development of SunThink has to face different challenges in the future, but also has promising aspects. Venetian blinds are light weight applications and newer developments of flexible thin-film cells allow realization of SunThink systems without any limitations in user comfort. Future research topics are:

- Tracking automation of the prototype;
- Detailed measurements on summer data;
- Development of thermal efficiency curves for air collector behavior;
- Detailed simulation of the curved louver profile, exact determination of the optimally equipped louver area.
- Adaptation of the prototype to flexible PV.

6 ACKNOWLEDGMENTS

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