GCLE
EXE Energy Industry Co. Ltd

3M Light Redirecting Film (LRF) → Durable Light Management Solution for Solar Module Efficiency Improvement

Abstract

3M Light Redirecting Film (LRF) is an engineered film that provides a new way to increase solar module power and energy output. LRF can be applied in non-active areas of the solar module during the assembly process to redirect light onto the active area of solar cells. In the lead application discussed in this paper, 3M LRF is applied over the film structure to achieve the best power and annualized energy gain, regardless of the orientation of the module once its installed. The film's performance has been rigorously tested and validated by module manufacturers and third party industry testing agencies. Extensive materials formulation and manufacturing process optimization ensures the film is durable and reliable. Modules using LRF have been tested up to three times the relevant IEC standard. In addition, more than five years of outdoor weathering at geographically diverse test locations show no film degradation, while robust and proprietary accelerated weathering testing completed by 3M has further demonstrated LRF will perform in the field. Since commercial launch in late 2016, more than 20GW of modules have incorporated LRF with minimum or no yield and throughput loss when compared to standard module manufacturing processes. Module manufacturers report power gains of 1.5-1.8% from LRF.

1. Background information

In the past several years, efficiency improvement has become a critical driver to reduce $/W in the solar module market. Advanced solar cell technology has been rapidly adopted by the industry. Light management provides another avenue to improve module efficiency in addition to solar cell-level advancement. In a typical solar module, up to 15% of the area is non-active (e.g. tabbing ribbon, cell and string gaps), so incident light falling on those parts of the module is not being converted to electricity. Incorporating LRF helps address the non-active area through optical means. However, the light management solution must be durable and reliable to withstand the conditions faced by solar modules in the field. In addition, the solutions need to be readily integrated into the manufacturing process. 3M is the first company to introduce a light management film solution (LRF) for application over the tabbing ribbons, which has been proven in terms of both performance and manufacturing with over 20GW of LRF modules deployed to date.

2. Optical design principal behind 3M Light Redirecting Film

The design of LRF is based on the principal of total internal reflection (TIR), which uses the refractive indices of the material used in a typical solar module laminate to redeploy otherwise-reflected sunlight onto the active portion of the solar cell. The refractive index of the front glass and EVA used in typical modules is about 1.5. The critical angle between glass and air interface to achieve TIR is 42 degrees or greater. Therefore, the LRF structure is designed to reflect incident light at a 60 degree angle to the glass/air interface (Fig. 1).

Fig. 1 shows the optical principle of the film.

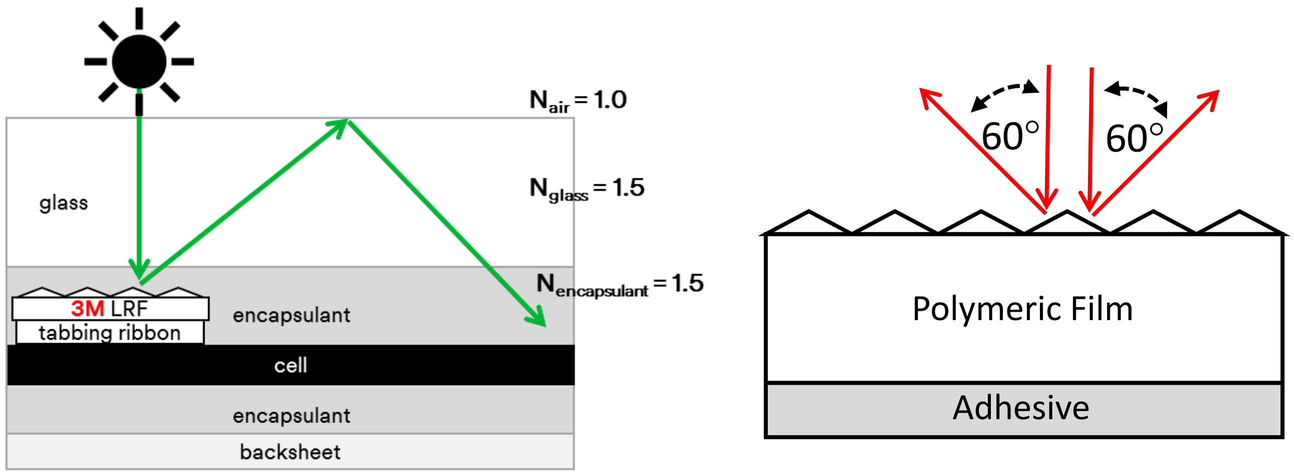


Fig. 1. LRF reflects and redirects light at high angle towards glass/air interface, where the light is totally internal reflected (TIR) onto active solar cells.

Quantum efficiency of film validates design

In order to validate the optical design of LRF, the National Renewable Energy Lab (NREL) in Colorado, USA, completed a controlled experiment to measure the quantum efficiency of the film. Single-cell modules with LRF over the tabbing ribbons were tested using Laser Beam Induced Current (LBIC, SEMILAB). Figure 2 shows images of the test. This test at NREL concluded that the quantum efficiency of LRF is more than 80% as efficient as the solar cell itself.

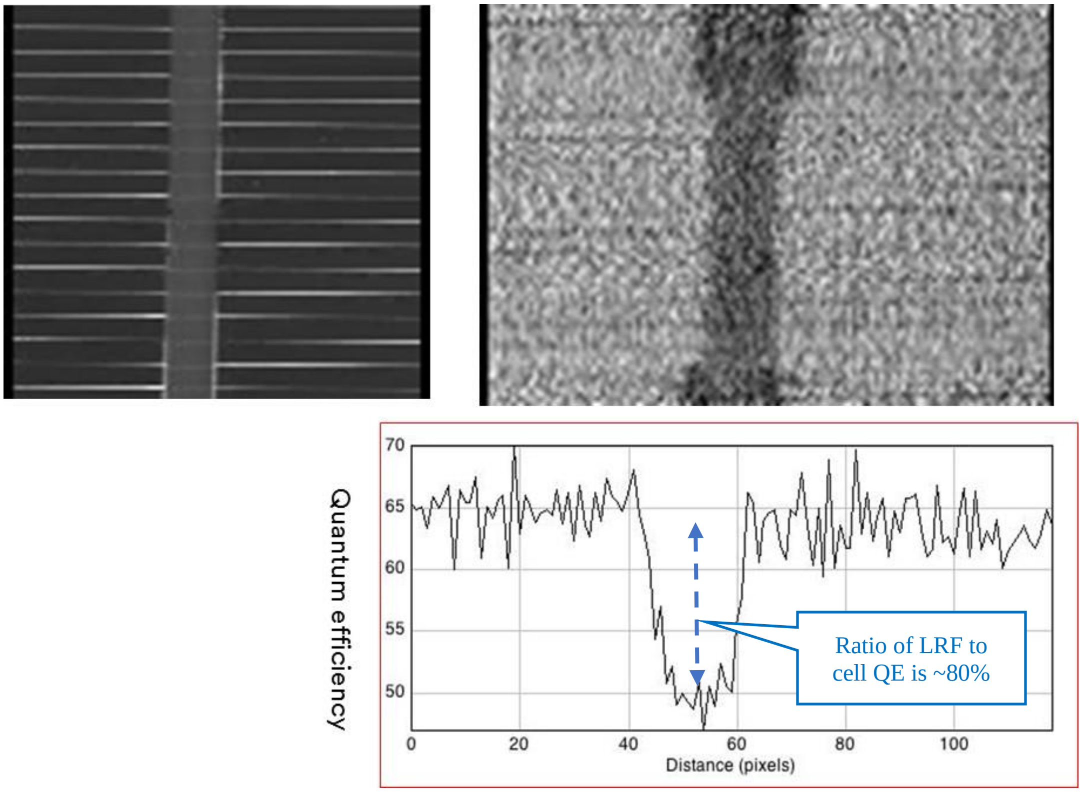
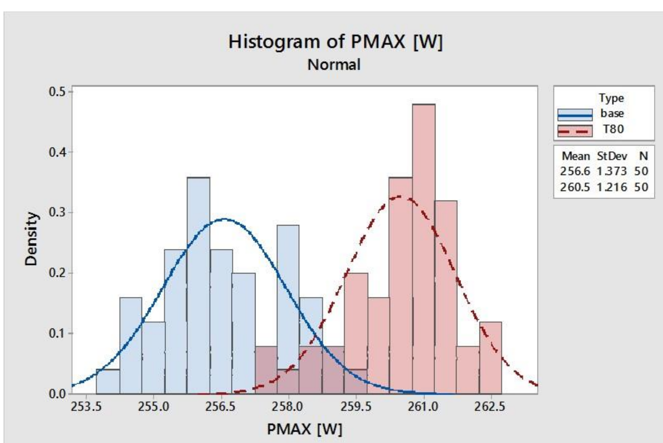


Fig. 2. Quantum efficiency image shows LRF is ~80% as active cell area.

3. Proven power gain and annualized field energy gain

Modules using LRF have been extensively tested by customers for power gain. For accurate power gain testing, a large number of modules is needed to show a statistically significant difference between baseline modules and LRF modules. Fig. 3 shows an example of one side by side test that resulted in an average Pmax gain of 1.5% from LRF.



Base Module:
- 4BB polycrystalline 60 cell module
- No LRF (exposed ribbons)

LRF Module:
- 4BB polycrystalline 60 cell module
- 2.0mm LRF T80

Fig. 3. 50 baseline modules and 50 LRF modules were built and tested in this example using PSAN solar simulator. The average 1.5% power gain was consistent with predicted value based 3M empirical modeling.

Commercial example: 385W modules

A 385W monocrystalline module design has been demonstrated by several leading module manufactures and is one of the highest efficiency modules in the market with proven manufacturing capability and capacity. To achieve this power rating, LRF over the tabbing ribbon is combined with 144 half PERC cells, as shown in Fig below.

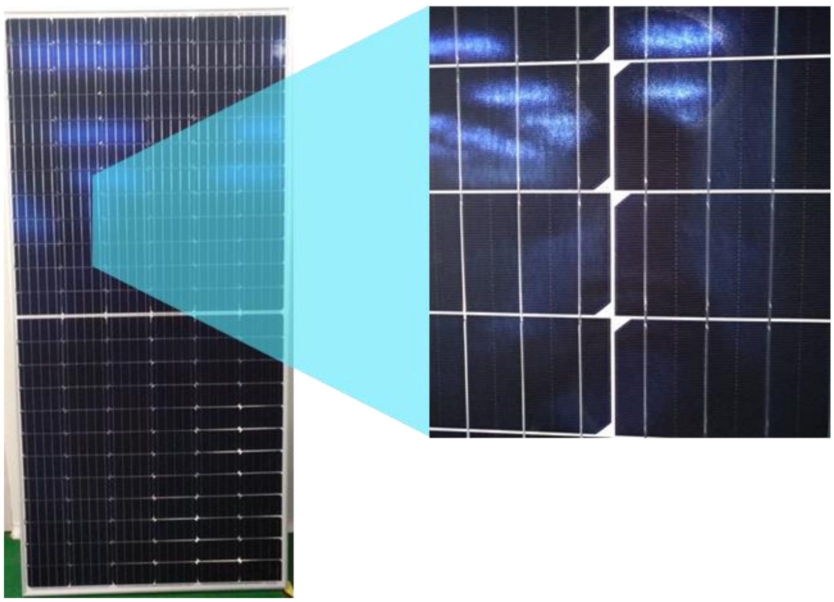


Fig. 4. 385W half PERC cell (144) + LRF over the ribbons module. Enlargement to show precise LRF alignment over ribbons.

Annualized energy output modeling, measurement, and test results

In addition to the instantaneous power gain, commonly referred to as the Flash Test gain, the film is optimized for annualized energy gain by using sophisticated modeling as input to the optical design, as summarized in Fig. 5.

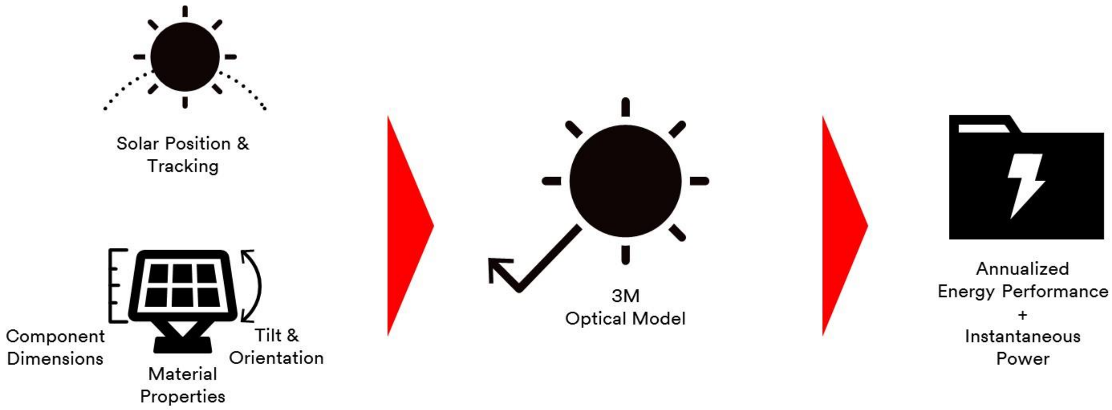


Fig. 5. Annualized energy gain optimization model inputs include: solar angle, module tile and orientation angles as well film properties.

Effectively and accurately measuring annualized energy gain attributable to LRF is more complicated than the instantaneous, or flash, gain. The following needs to be considered:

1) The performance difference between baseline and LRF modules must be measurable
2) Testing equipment must be carefully calibrated to have large linear response to light intensity. Typically, early morning and late afternoon prove to be more challenging due to low light intensity and large angle of incidence
3) Testing location is free of shadowing and surrounding light interference during the extended testing period. Nearby buildings and grounds are all possible sources of light which affects the light incident onto baseline and LRF modules
4) Testing period must be long enough to overcome non-uniform irradiation due to clouds and thermal difference due to wind
5) Data must be carefully analyzed by independent experts to filter out noise

To validate the effect LRF had on the field energy performance of modules, a controlled study by TUV Rheinland, Shanghai lab, was carried out between 08/15/15 - 11/27/15. Data from this controlled study show that LRF modules generated on average 1.86% more field energy compared to baseline modules containing no LRF. Fig. 6 shows the results and includes the flash test results from TUV Rheinland, Shanghai, as well.

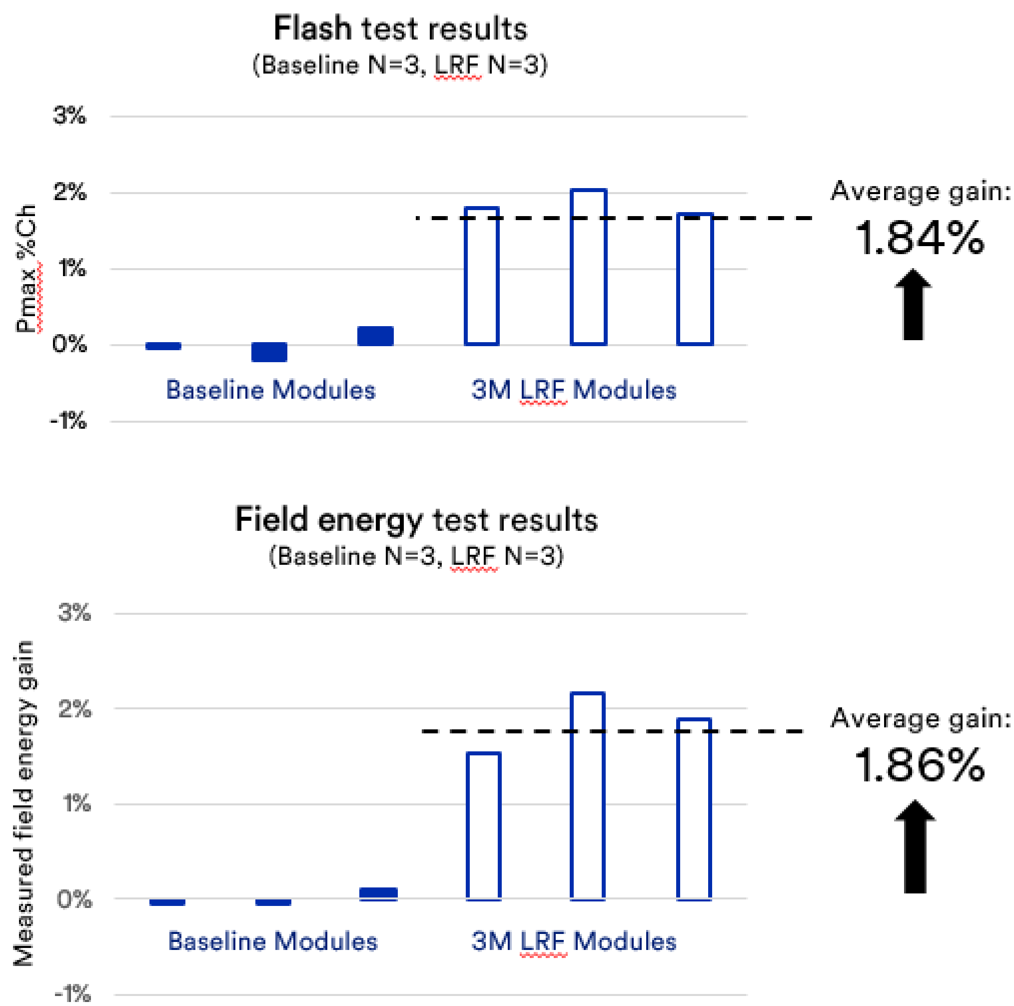


Fig. 6. Three baselines and three LRF modules were built and tested between 08/15/15 - 11/27/15 in Shanghai, China

4. Film is designed to meet long-term durability and reliability requirements

Typical solar modules have a service life that extends beyond 25 or 30 years. Material that are incorporated into the module, such as LRF, must satisfy all industry standards for durability and reliability testing. Most importantly, they must deliver on performance in the field over the life of the module. The following was incorporated into the design of LRF with that long-term durability and reliability need in mind:

1) Materials are formulated so that they are chemically compatible with existing materials inside solar modules. For example, PET is used as the base substrate, which is present in most commercially available solar back sheets, and an EVA is chosen as the adhesive, which is widely used as an encapsulant in the industry. All critical LRF materials are formulated and made by 3M

2) Durability to UV light: A thin and durable layer of aluminum (Al) is deposited onto the micro structure and faces the sun. This Al layer blocks harmful light from reaching the polymer material while providing the required reflective properties of the film
3) The micro-optical structure must be thermally stable. This is critical to maintain the optical performance of LRF for the lifetime of the solar module
4) The LRF manufacturing process is carefully controlled to provide precision and consistency in the product, which inherently contributes to long-term durability and reliability in the application.

The final material set used in the 3M LRF product construction is the result of a robust down-selection process that evaluated a wide range of materials and processing conditions.

5. Data from 5+ years of outdoor weathering and application of 3M weathering science to LRF

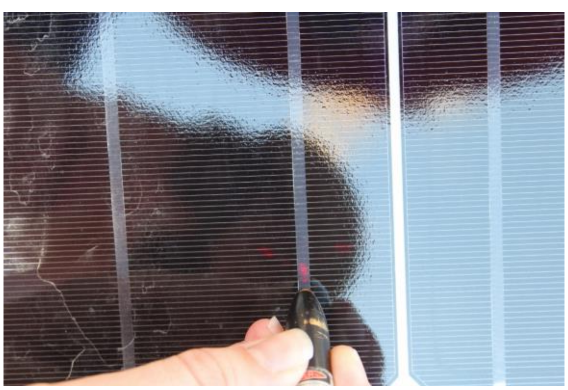
Roughly 25% of 3M's annual global sales come from products that require outdoor durability. 3M has built a world class weathering research center with a staff of dedicated weathering scientists and the world's largest accelerated weathering laboratory located in St. Paul, Minnesota, USA. The development team for LRF leveraged the weathering expertise of 3M to inform decisions on materials selection and the final product construction.

Outdoor testing started early in the product development process. Solar modules containing LRF were placed in selected outdoor exposure sites across the United States, representing three different climate conditions. Miami Florida was chosen for its extreme heat and humid environment. Arizona was chosen for extreme UV and heat condition. Finally, Minnesota was selected for its extreme cold and humid environment.

After more than 5 years outdoor exposure, no degradation has been observed in the LRF, the optical structure is still redirecting light as expected (Fig 7), and electrical tests confirm that modules with LRF are performing consistently over time (Fig. 8).

Figure 7. Images of laser pointer on LRF demonstrating optical performance after 5 years in the field (images taken July and August 2018, respectively)

Arizona, USA



Florida, USA

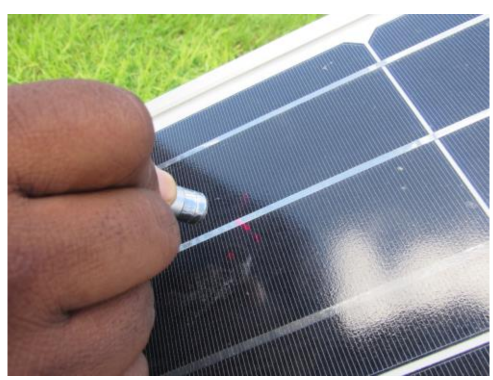
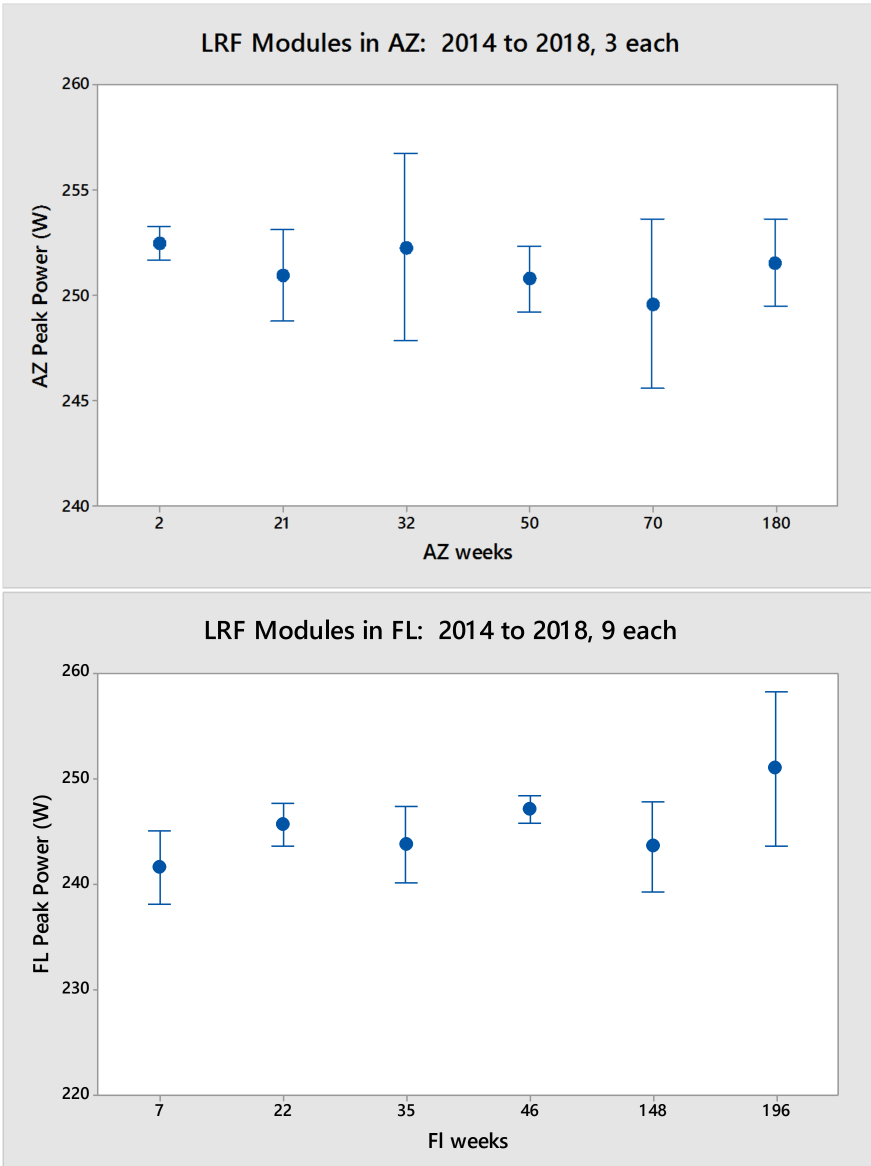


Figure 8. LRF module power measurements by week show consistent Peak Power (Daystar 100C IV curve Tracer) over time indicating no degradation in LRF performance after 180 and 196 weeks, respectively



3M plans to continue observing and testing these modules for the foreseeable future to build a long-term data set for LRF and its future derivatives.

6. Simple integration into existing manufacturing process

Solar module manufacturing has achieved very high yield efficiency and throughput, achieving annual production of more than 100 GW. It is important and beneficial for any new technology to be readily integrated into existing processes without impacting yield and throughput in a highly competitive and scaled industry. The LRF applicator is a unit that can be added into the space available in exiting stringer equipment common in the industry. In the module assembly process, LRF is applied over the tabbing ribbons immediately after ribbons are soldered to the cells and can currently address cells with 3, 4, or 5 busbar configurations. The adhesion of the film over the ribbons is instantaneous after physical contact and, therefore, does not limit throughput. In addition, the proprietary adhesive used in LRF enables the film to stay on the ribbons after precise placement and maintain its registration over the tabbing ribbon through the subsequent process steps in module layup and lamination. The capital investment is relatively low at just a fraction of the cost of the total stringer equipment. In many cases, LRF applicators can be retrofit onto existing manufacturing lines.

7. Critical adhesive properties: Strong enough to minimize drift but soft enough to minimize stress on solar cell

LRF is applied over the tabbing ribbons, which is a well-known stress point on cells. Therefore, it is critical that the adhesive does not provide extra stress onto cells as polymer films have less thermal stability than solar cells. On the other hand, the adhesive must be strong enough so the film stays on the ribbons and does not drift during subsequent processing steps including thermal lamination. Drift affects both power gain and appearance. Drifted film will cover active solar area, which decreases the power instead of increasing the power.

Fig. 9 shows the quantum efficiency drop with drifted LRF and the appearance.

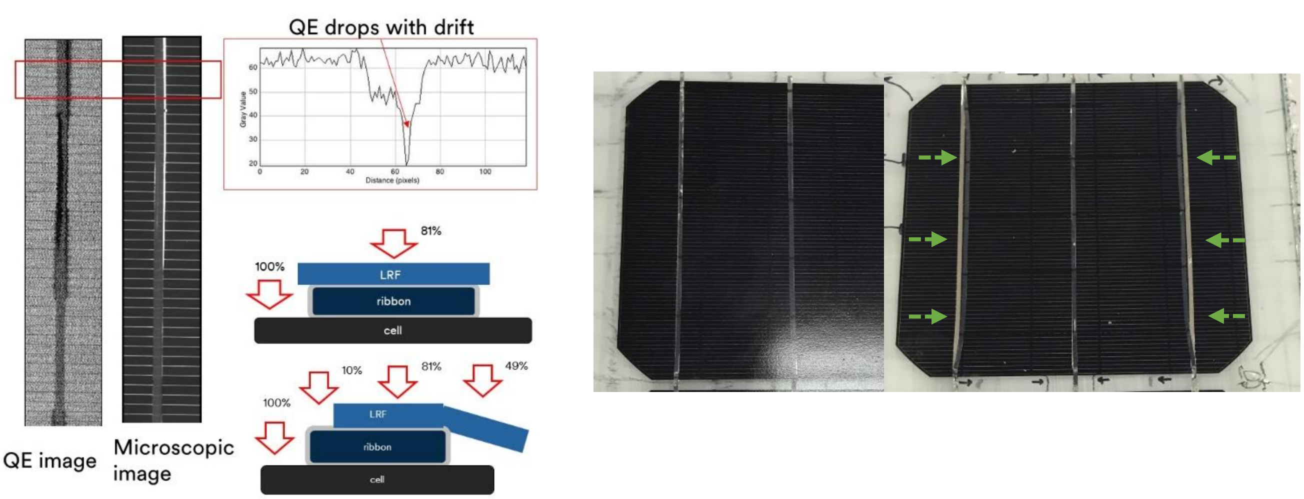


Fig. 9. QE image shows significant drop in efficiency with drifted film. The right pictures show the appearance difference between drifted and LRF film.

The adhesive used in LRF film is carefully formulated to meet the above criteria and remain easy to apply over the tabbing ribbons in a mass production environment.

A simple method modified from ASTM D3654 / D3654M to test adhesive has been developed to assess drift resistance performance before lamination. Strips of LRF film

(1/4" wide) are applied over Al foil. A 1 kg weight is attached to the strips. The samples are placed into a 150-degree C oven, as shown in Fig. 10. LRF with typical EVA falls within 2 minutes. Specially formulated LRF adhesive does not fall after 10 minutes of exposure to the test condition.

Fig.10. Oven testing of adhesive before lamination for minimum drift.

8. Conclusions

3M Light Redirecting Film (LRF) provides a new way to increase solar module efficiency. By addressing the non-active portion of the solar module, in this case the tabbing ribbons, with durable optical films, module OEMs can achieve a 1.5-1.8% gain in power output irrespective of baseline cell efficiency. 3M LRF has been carefully designed and developed to provide this optical gain consistently and for the life of the film in the solar module. More than five years of outdoor exposure (combined with rigorous proprietary accelerated weathering testing) showed no degradation in terms of appearance or performance. The benefit from LRF extends to increased field energy production as validated in a controlled study conducted by TUV Rheinland, Shanghai lab. And finally, achieving the power gain with LRF over the tabbing ribbon requires a specially formulated adhesive that allows the LRF to be applied at the speed of module mass production and maintain its position over the tabbing ribbon through the module assembly and lamination process.