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2.5 MINUTES LAMINATION PROCESS AND THE INFLUENCES OF THE DEGREE OF CROSS-LINKING AND THE MOISTURE INGRESS ON THE DEGRADATION OF PV MODULES

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ABSTRACT: Faster lamination processes and more sustainable modules will play a critical role to meet the industries demand for green energy. This study presents the influences of short lamination processes on the moisture balance, achieved by increasing the lamination temperature up to 180 °C, and compares these with modules laminated at a common lamination temperature of 150 °C. The investigations are conducted mainly on mini modules, but additionally to those also a standard 60 cell module is built and exposed to the damp heat (DH) test to have a better understanding of the influences of the fast lamination process. The mini modules were exposed to DH for 1500 and 3000 hours and were measured before and after the accelerated ageing in terms of IV measurements and peel tests. We observed no severe degradation caused by the higher lamination temperature in terms of moisture ingress. During the study we also investigated the cost of the 2.5 minutes curing process and discussed the potential benefit for module production facilities. The results of the simulation showed that module manufacturers could reduce their module costs up to 1.3% per module with the faster process.
Keywords: PV Modules, damp heat, degradation, economic analysis, manufacturing

1 INTRODUCTION

The lamination process is one of the most critical steps that influences the quality of a photovoltaic (PV) module in terms of long term stability [1]. In order to provide operational product lifetimes of at least 20 years, the lamination process should ensure a proper adhesion between the laminate layers and a certain degree of crosslinking [2]. Common methods for the quality control of the lamination process is performing peel tests and measuring the degree of crosslinking of the PV modules [3]. However, the lifetime of a module in terms of encapsulation material processing is mainly influenced by the moisture ingress and its resulting consequences that occur during the operational lifetime of a module. The amount of the moisture ingress can be reduced by using edge sealing or encapsulation materials with a high-water vapor transmission rate (WVTR) [4]. Todays most widely used encapsulant is ethylene vinyl acetate (EVA) which has a market share of around 70% [5]. The moisture that enters the module can react with the EVA in the form of hydrolysis and generates acetic acid. The generated acetic acid causes corrosion and leads to a decrease in performance of the modules [6]. Polyolefins are an alternative to EVA and are preferred for laminating SHJ cells or for the glass-glass layup [7]. For the next years, the PV market is expected to keep continue its increasing trend [5]. To meet the demand of PV modules, manufacturers are trying to shorten the lamination process [1]. This can be achieved by using higher lamination temperatures [8].
This study focuses on laminating at 180 °C and the long-term influences of this lamination processes in terms of moisture ingress. To observe the long-term effects, the modules underwent the damp heat (DH) test. The aim of the DH test is to insert moisture into the module to accelerate the ageing process [9,10]. The modules are then evaluated in comparison to modules from the standard temperature lamination processes in regards of performance, and adhesion forces before and after the DH tests. Additionally, three different gel contents and their influence on the degradation behaviour and the productions costs of the 180°C lamination process are analysed.

2 MATERIAL AND METHODS

2.1 Sample Preparation

For this study, a total of 63 mini modules in the sizes of 280 mm x 250 mm were fabricated by using a Bürkle-Ypsator laminator. To protect them from humidity ingress through edges, an edge sealant was used. To analyse the influences of the moisture ingress and its relation to the gel content two different backsheets, one with a high WVTR and one with a low WVTR were chosen. These modules were built with moisture-sensitive heterojunction (SHJ) solar cells at a lamination temperature of 150 °C. Three different lamination duration times were used to get a degree of crosslinking of around 60, 70, and 80%. For the investigations of the short lamination process modules were cured at a peak lamination temperature of 180 °C for again three different lamination duration times. These modules were built with PERC cells and the low WVTR backsheet. In addition to these mini modules a standard-sized module with 60 PERC cells and the same low WVTR backsheet was built and tested in DH1000 to analyse the influence of the 2.5 minutes curing process on a standard module. All modules were laminated with a polyolefin elastomer (POE) encapsulant to protect the moisture-sensitive heterojunction (SHJ) solar cells. The specifications of the materials used in this study are shown in Table 1.

Table 1: List of used encapsulation materials and their specifications

Layer	Material	Thickness [mm]	WVTR [g/m² x day]
glass 1	tempered glass	3	0
glass 2	solar glass	3.2	0
backsheet 1	PET/PET/Primer	0.493	<0.5
backsheet 2	PET/Primer	0.218	<2.2
encapsulant	POE	0.68	n.a

In order to have reliable results, seven prototypes were built for each combination. Three of them were used for the initial measurements, two for DH1500, and the rest for DH3000 testing. The overview of the fabrication and characterization process is shown in Figure 1 and Figure 2.

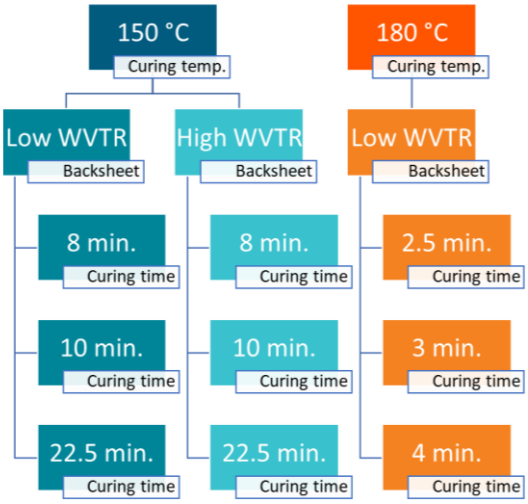


Figure 1: Lamination process specifications of the prepared samples

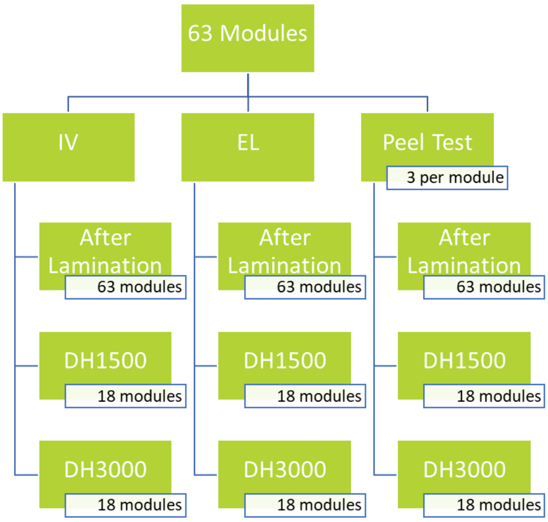


Figure 2: Module characterization methods and number of samples for each degradation condition

2.2 Soxhlet Extraction

To identify initial process durations and determine the degree of crosslinking of the modules, the Soxhlet extraction method was applied based on EN ISO 10147 and EN ISO 6427. It is an easy method that determines the degree of crosslinking by measuring the gel content before and after the extraction. In the PV industry, it is used for the development of new processes and quality control [11]. The serial extraction apparatus from Behrotest shown in Figure 3 was used for the Soxhlet measurements in this study.

Figure 3: Serial extraction apparatus from Behrotest

2.3 Flasher Measurements

The initial characterization as well as the performance of the modules after the ageing tests were observed by current-voltage (IV) curve measurements with a WaveLabs flasher. The standard-sized module was measured at Fraunhofer ISE TestLab PV Modules according to IEC 60904-1 and IEC 60904-3.

2.4 Electroluminescence (EL) Measurements

To characterize the modules and analyse the influences of the moisture ingress in the cells, EL images of all modules are taken after certain periods. This allows us to make a correlation between the decrease in module performance and the moisture ingress into the module.

2.5 Peel Tests

The peel tests in the study were conducted at the glass-encapsulant interface by using the peel-off instrument manufactured by PSE. All peel test measurements of the mini modules were done according to the BS EN ISO 8510 standard [12]. Three strips with a width of 10 mm each were cut along the module surface and were measured with a peel angle of 90° with a speed of 50 mm/min. The relative maintained peel force (RMPF) which is used for the evaluation is determined by the following formula [8]:

$$RMPF = \frac{Peel\ force\ after\ DH\ 3000}{Initial\ peel\ force}\ x\ 100\%$$

2.6 Accelerated Ageing

For long-term investigations of the module performance, damp heat (DH) tests were conducted. The DH test is a standard method for ageing polymer materials used in PV. The modules were exposed to DH (85 °C, 85%r.h.) for 1500 hours and 3000 hours. This method was chosen, because it degrades the modules by moisture ingress into the module from the environment and allows us to compare the difference of the low WVTR and the high WVTR backsheets [3].

2.7 Energy Consumption and Cost Calculation

Analyses of the energy consumption of both, the short lamination process and a typical industrial process, (at 155 °C) were conducted by Robert Bürkle GmbH. Ten runs were done with a Bürkle Ypsator laminator for each process. The energy consumption per module was calculated with the following formula:

$$Energy\ per\ module = \frac{energy_{heating} + energy_{\text{switching cabinet}}}{\text{number of modules}}$$

The impact of changes in energy consumption and increased cycle time are analysed using the "SCost" cost model developed by Fraunhofer ISE [13]. The model calculates the Cost of Ownership (COO) for a module or manufacturing site based on module design information (e.g., cells per module, layers, size, etc.), equipment, and process parameters (e.g. cycle times, breakage rate, equipment availability, utility consumption, etc.) and additional information (e.g. taxes, costs for infrastructure, capital costs, etc.). The model is based on SEMI E10 and E35 standards.

Slower and faster lamination process together with their specific energy consumption and other equipment parameters have been modelled and the impact of the changes in the process have been analysed with regard to the impact on the costs of lamination (see Table 2).

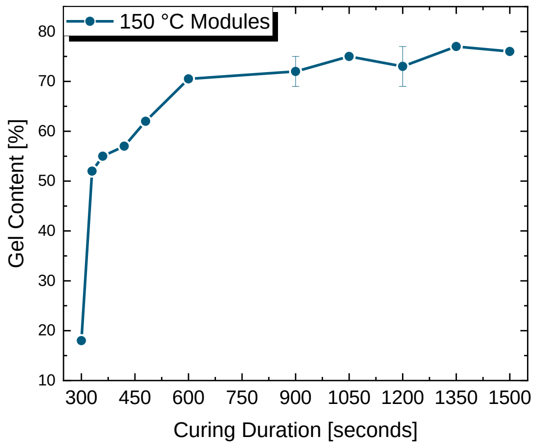
Table 2: List of inputs for process cost modelling

	Fast process	Slow process	
Equipment price	610.000	310.000	€
Cycle time	7.5	14	min/module
Electricity consumption	34.2	33.7	kWh/h
Personnel	0.05	0.05	Persons/shift
Floor space	246	246	m²
Equipment uptime	94%	94%	
Breakage rate	0.2%	0.2%	

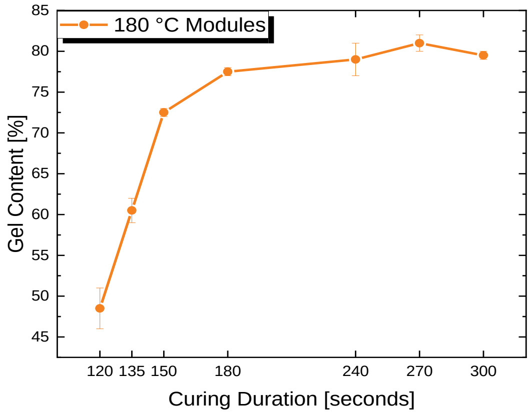
3 RESULTS

3.1 Soxhlet Extraction

To decide the lamination durationtime and reached gel contents of around 60, 70, and 80% for the 150 °C lamination process Soxhlet measurements were done for certain curing durations. The goal for the 180 °C lamination process was to reach reliable gel contents with a short curing time. The behaviour of the gel content of POE versus the duration time is shown in Figure 4 for the two lamination temperatures of 150 °C and 180 °C.



(a)



(b)

Figure 4: Gel content measurement results in samples manufactured using different process conditions, (a) 150 °C lamination temperature, (b) for 180 °C lamination temperature

The gel content of the modules laminated at 150 °C in Figure 4 (a) showed a logarithmic behaviour between 300 and 600 seconds. After this period, it became more consistent and reached a gel content of around 75%. To reach approximately the required three gel contents (60, 70, 80%), the curing duration time was set to 480 (62%), 600 (70.5%) and 1350 (77%) seconds, respectively.

For the modules laminated at 180 °C it was observed that the period from 120 to 150 seconds plays a critical role for the degree of cross-linking, whereas after only 180 seconds it roughly reaches its saturation point. With respect to the results shown in the Figure 4 (b), 150, 180 and 240 seconds were chosen as lamination duration times with high potential to pass the further tests.

3.2 Performances before/after Accelerated Ageing

This section analysis the influences of the moisture ingress that took place during the DH test on the performance of the modules, which were laminated under various lamination conditions. The degradation of module performances over time is shown in Figure 5.

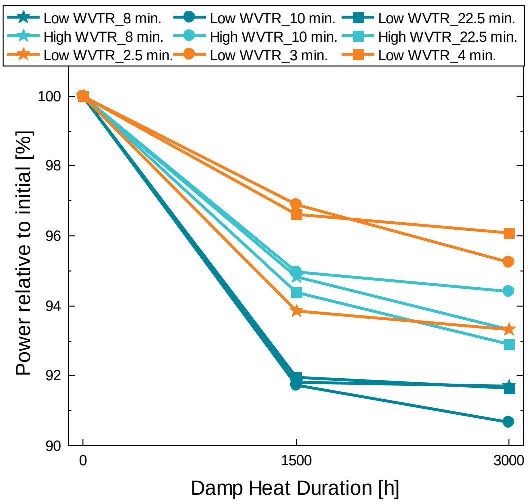


Figure 5: Module performances ratio before to after the DH test. Please note, that the orange curves are obtained

with PERC cells and the blue curves are obtained with SHJ cells.

Figure 5 shows that all mini modules are mainly influenced during the first 1500 hours of DH. It is seen that the degradation rate from DH1500 to DH3000 is much lower compared to the degradation that takes place in the first 1500 hours. It is also observed that there is a trend for the loss in performance with respect to the backsheet. It is found that all modules laminated at 150 °C with the high WVTR backsheet had a higher relative power after both the DH1500 and the DH3000 tests compared to the modules with the low WVTR backsheet. When comparing the results of the low WVTR backsheet for the 150 °C and 180 °C processes, it can be observed, that the 180 °C processes performed better with less degradation values, as expected of the more moisture robust PERC cells used for the 180 °C process. Also, as it is seen in Figure 5, the only modules which show a degradation lower than 5% after DH3000 test were the ones laminated at 180 °C with curing times of 3 and 4 minutes. The only outlying result for the 180 °C processes is the 2.5 min curing process, which has a lower performance to the others.

After evaluating the IV measurements of the mini modules that were exposed to the DH test, visual analysis was conducted on them. The results are shown in Figure 6 below.

(a)

(b)

Figure 6: Discolouration of the 150 °C modules after DH1500, laminated at 8 min, 10 min and 22.5 min, respectively, (a) low WVTR backsheet, (b) high WVTR backsheet

The visual inspections showed that there are differences in terms of discolouration mainly between the two backsheet types, but also between the lamination time, especially for the low WVTR backsheet. Figure 6 (a) which presents the discolouration of the modules laminated with the low WVTR at 8, 10, and 22.5 min curing durations shows that there is a trend in discolouration from low gel content to high gel content. The modules with lower gel content discoloured much more than the modules with higher gel content. The same trend is also obtained in the modules laminated at 180 °C and the ones which used the high WVTR backsheet (not shown here). Whereas at the high WVTR backsheet it is not as clear to see as it is for the low WVTR one. But instead, Figure 6 (b) shows that the moisture ingress probably mainly took place from the edges of the mini modules, because the discolouration at the edges and especially at the corners is stronger compared to the centre of the modules. This phenomenon might also explain, why the module with the 180 °C / 2.5 min process in Figure 5 has significantly lower performance, compared to the ones with higher gel content. Its performance could be lower, because of the higher discolouration and reduction in transparency.

To have a better understanding of the fast lamination process and its long-term influences, a standard 60-cell glass-backsheet module was laminated at 180 °C with the 2.5 min curing process exposed to DH1000. The only difference between this module compared to the mini modules was that it had a frame to protect it from the moisture ingress through the edges instead of the edge sealant. The DH100 results of the Fraunhofer ISE TestLab, which are summarized in Table 3, showed that the degradation in power is less than 1% (below the testing accuracy), which indicates that the standard sized module laminated with the 2.5 min curing process passed the DH1000 test.

Table 3: Performance of the 60-cell module before and after DH1000

		Isc [A]	Voc [V]	Impp [A]	Umpp [V]	Pmpp [W]	FF [%]	Degradation of Pmpp [%]
60 Cell Module	Before DH 1000	10.076	40.609	9.473	32.842	**311.140**	76.038	0.73
	After DH 1000	9.979	40.694	9.370	32.962	**308.867**	76.056	

3.3 Electroluminescence (EL) Measurements

The EL images, of the PERC cells laminated from top to bottom with the 2.5, 3 and 4 minutes curing processes are shown in Figure 7, respectively. The left side shows the EL images before ageing, the right ones after DH3000.

Figure 7: EL images of modules laminated with the 2.5, 3 and 4 min curing processes before and after DH3000

Slight differences in grey scale can be noticed for all modules. The most certain one, however, occurred at the 2.5 min process. Here darker zones at the edges of the module are observed after DH3000. These indicates the ingress of moisture into the module which causes degradation and loss in performance. This result also matches with the one in Figure 5.

The EL images of the standard-sized 60 cell module are shown below. The initial image is represented on the left side, the result after DH1000 on the right.

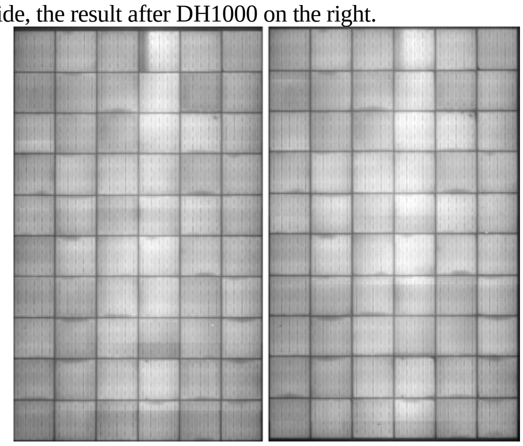
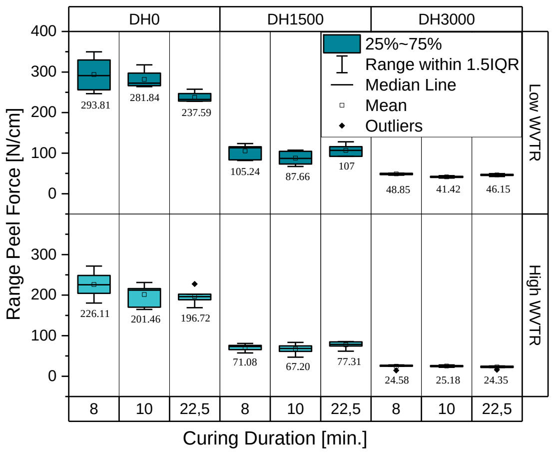


Figure 8: 60 cell module before andafter DH1000

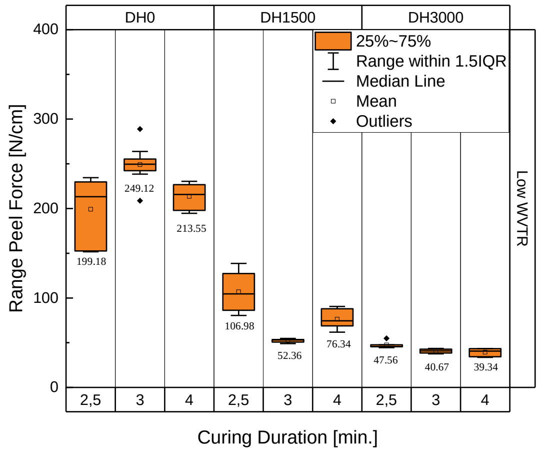
As seen in Figure 8 there are some small defects, but most of them were already there before DH1000. The cells at the edge seem not to be affected that much by moisture compared to the mini modules laminated using the same process.

3.4 Peel Tests

For the peel tests, 3 measurements were done at the glass-encapsulant interface of each module, next to the cells. The overview of the results for the 150 °C processes and the 180 °C processes are shown in Figure 9 (a) and Figure 9 (b), respectively. The time when the measurements were conducted on top of the graph, the duration time of the curing process on the bottom, and the colours of the boxes are done according to the same systems applied in Figure 1.



(a)



(b)

Figure 9: Peel force at the glass-encapsulant interface before and after DH1500 and DH3000 for (a) the 150 °C lamination process and the (b) 180 °C lamination process

Figure 9 (a) shows that the modules laminated with the low WVTR backsheet have always higher peel forces with respect to the ones laminated with the high WVTR backsheet. The difference between them, however, gets lower after accelerated ageing. Another point is that the highest peel forces, that are observed during the initial measurements for both backsheets are the ones with the lowest gel content (8 min curing).

The RMPF values after DH3000 for the 150 °C, low WVTR modules varied between 14.7 - 19.4% while the RMPF values for the 150 °C, high WVTR modules are with 11.7 - 12.5% lower.The modules laminated with the high WVTR backsheet reach only peel forces of around 25 N/cm.

The peel forces of the modules laminated at 180 °C shown in Figure 9 (b) look more distributed than the 150 °C ones. Initially, lower peel forces at 180 °C lamination as compared to lamination at 150 °C are observed. However, after DH3000, they perform similar to the 150 °C, low WVTR (45.5 N/cm) modules and get peel forces of around 42.5 N/cm. Therefore, we conclude that the lamination temperature does not negatively influence the peel forces after ageing with DH3000. A correlation between the gel content and the RMPF was not observed.

3.5 Energy Consumption

The comparison of the short lamination process at 180 °C with a commonly used lamination process in the industry at 155 °C, showed that, using the new process would cause an increase in energy consumption, due to the higher process temperature. However, through the short process time, the production rate of PV modules would be much higher than with the slow processes. This results in an increased number of modules per day effectively reducing the energy consumption per module. The analysis showed that there is a potential to reduce the energy consumption per module by approximately 46% by using the short lamination process.

The reduction of energy consumption reduces the costs for electricity. While energy costs are responsible for 23% of the total process costs in the slow process, they only make up 17% in the fast process.

Additionally, much higher benefits than energy saving can be found through additional effects on other cost factors, especially infrastructure/facility and labour costs. Those can be considered fix, meaning that they are not significantly impacted by the choice of process. Since the faster process allows for a higher manufacturing output, the lamination costs per module are therefore reduced (see Figure 10).

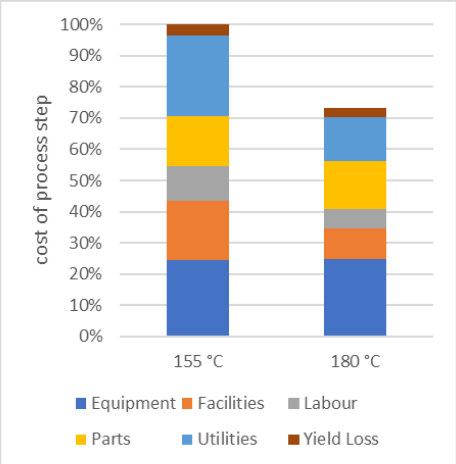


Figure 10: Cost structure of both lamination processes

We find that the increased cycle time effectively reduces the costs of lamination by 27%. Considering that the lamination process step accounts for 5.8% of the total module costs in our calculation, the benefits of the 180 °C, 2.5 min curing process led to a cost advantage of 1.3% in module costs (€/module and €/W_p).

4 CONCLUSION

In this work, we studied the long-term influences of the fast-curing process in terms of moisture ingress, and we simulated the energy consumption and changes in module costs with the "SCost" model of Fraunhofer ISE. Additionally, the influences of the degree of crosslinking and moisture ingress on the degradation of the PV modules were analysed regarding the module's performances and peel forces. The study was conducted on mini modules, which were laminated at different curing duration times to get different levels of gel contents and by using two different backsheets, which had a low and a higher WVTR.

The peel test results indicate that the modules with the low WVTR backsheet have also higher RMPF values after DH3000. When comparing the RMPF values of the 150 °C and 180 °C lamination processes it is seen that they vary between 14.7 - 19,4% and 16.3 - 23.9%, respectively. This means that the peel forces of the 180 °C processes degraded slightly less than for the 150 °C process.

The IV results of the modules laminated at 150 °C showed that the modules with the high WVTR backsheet degraded less than the modules with a low WVTR backsheet. The visual inspection revealed that all modules with the low WVTR backsheet discoloured more than the ones with the high WVTR backsheet. The decrease in reflectivity might be the main cause for the higher loss in performance. The discoloration can be in correlation with the oxygen transmission rate and the WVTR characteristics of the backsheets. It might be that the moisture, that seems to have entered the modules from the edges, could leave the modules with the high WVTR backsheet easier through the backsheet, causing less discoloration. More investigations need to be done to have a better understanding of this phenomenon.

The standard-sized 60-cell module cured for 2.5 minutes showed a loss in performance of less than 1% after DH1000.

The energy consumption and economic analysis showed that the energy consumption of the 180 °C process is a little higher than for the 150 °C process, but due to its fast production rate, the energy consumption per module would reduce by approximately 46%. The simulation also showed that the module costs (€/module and €/W_p) could be reduced up to 1.3% by using the fast lamination process.

It can be concluded that the fast lamination process at 180 °C has many benefits in terms of energy consumption and cost reduction per module. It was also shown that a full-size module manufactured with the process does not show any significant degradation after DH1000.

5 ACKNOWLEDGEMENT

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