Final Scientific Report for DOE/EERE

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Executive Summary

This project was designed to address the Solar Energy Technology Program objective, “to develop new methods to integrate photovoltaic (PV) cells or modules within a building-integrated photovoltaic (BIPV) application that will result in lower installed cost as well as higher efficiencies of the encapsulated/embedded PV module.” The technology assessment and development focused on the evaluation and identification of manufacturing technologies and equipment capable of producing such low-cost, high-efficiency, flexible BIPV solar cells on single-ply roofing membranes.

This research added to the understanding of adhesion requirements for flexible PV modules and components to single ply roof membranes with an emphasis on delineating balance of system costs such as electrical and hardware labor costs. This project benefits the public in that and material property requirements were evaluated against adhesion and peel strength test protocals. Secondly, the field testing provided comparative, objective performance data on energy output in five distinct meteorological locations with three separate flexible PV technologies.

Carlisle Construction Materials’ (CCM) intent of this program was to develop these products requiring minimal transition from traditional roofing installation practices, while still having the ability to maintain water proofing and service life warranty of the roof. Various integration technologies were evaluated, including multi-layered roll lamination and vacuum lamination. These were evaluated both during and after production of the membrane as the base sheet, and included Carlisle’s manufacturing competencies as well as thin film or flexible PV cell technology as the basis for developing the encapsulation materials and lamination equipment.

Major accomplishments achieved during Year 1 include the following:

1.) Installation of test arrays in five separate climatic regions;
    a. Each test array was composed of three separate 1kW flexible, high efficiency PV modules.
    b. Each test array’s performance data was captured and analyzed to compare technologies.
2.) Procurement of a pilot scale custom lamination machine;
    a. The lamination machine also incorporates a roll-to-roll winder/unwinder system.
    b. The equipment can handle commercial width (10-12 feet) roof membrane.
3.) Design of an integrated DC wiring solution for module junction and string level connection;
4.) Demonstration of a proof of concept prototype commercial BIPV product; and
5.) Identification of a pathway toward an installed cost of $2.99/Watt by 2014.

Task 1: Investigate Technologies to be Incorporated into TPO-Backed Module

Under the first phase of the award CCM identified three potential U.S. based PV cell/module manufacturers: These Technologies will be designated Technology ‘A’, ‘B’ and ‘C’. CCM’s selection process was conducted through the creation of a metric sheet, shown on the following page in Table 1, to evaluate a number of selection criteria. Unfortunately, the selected c-Si vendor, Technology C, terminated its U.S. operations in May of 2012. Pending sales of technology A and B also caused CCM to engage other flexible module manufacturers for evaluation and testing of the BIPV project beyond the initial three identified above.

Module Manufacturer Evaluation Metric

The table below illustrates portion of the metric for evaluation of module manufacturer appropriateness for the BIPV application, based on key criteria such as cost, availability, and performance.

Table 1: Manufacturer Evaluation Metric –

Company Name	Efficiency	Cell Technology
Global Solar	12.50%	CIGS
Fuji	6.30%	aSI
MiaSole	14.40%	CIGS
Ascent	10.70%	CIGS
Transform	14%	cSi
Konarka	3-4%	Organic
HighFlex Solar	19%	cSi (Mono)
Alta Devices	23%	GaAs

As a part of this evaluation, CCM subjected test samples of the three PV cell vendors to a number of lab and field tests. The lab tests and subsequent results were reviewed in detail under Task 4 of the Statement of Project Objectives (SOPO).

Under this evaluation process, CCM constructed and installed five separate test array systems. The locations were chosen to provide testing in a diverse set of weather conditions. The locations include five separate and metrologically diverse set of Carlisle locations labeled as Locations 1, 2, 3, 4 and 5.

These installations include monitoring capacity to measure insolation, DC, and AC output as well as humidity and temperature. The installations were completed on May 25, 2012. The analysis in Table 2 on the page (5) represents 30 days of information compiled from these test arrays.

Figure 1: Photos of CCM's five test arrays, installed at the following sites:

Location 1

Location 2

Location 3

Location 4

Location 5

Test Array Data & Analysis -

Monitoring of the test arrays focuses on two separate areas of interest: array performance and energy production. The first area of interest is the performance of the array as it pertains to the manufacturer's published data. CCM compared the nameplate rating of the modules with the specific output of the array in DC volts, amps and watts. The team also used the temperature compensation factor to calculate the expected output for the available light and cell temperature. Losses due to cables and connectors were not included. During installation, cable lengths were minimized to be within 30 feet between the arrays, making losses less than 1%. In all cases, the arrays performed within 10% of their corrected rated output. In some cases, the modules exceeded their corrected rating as shown in the table below.

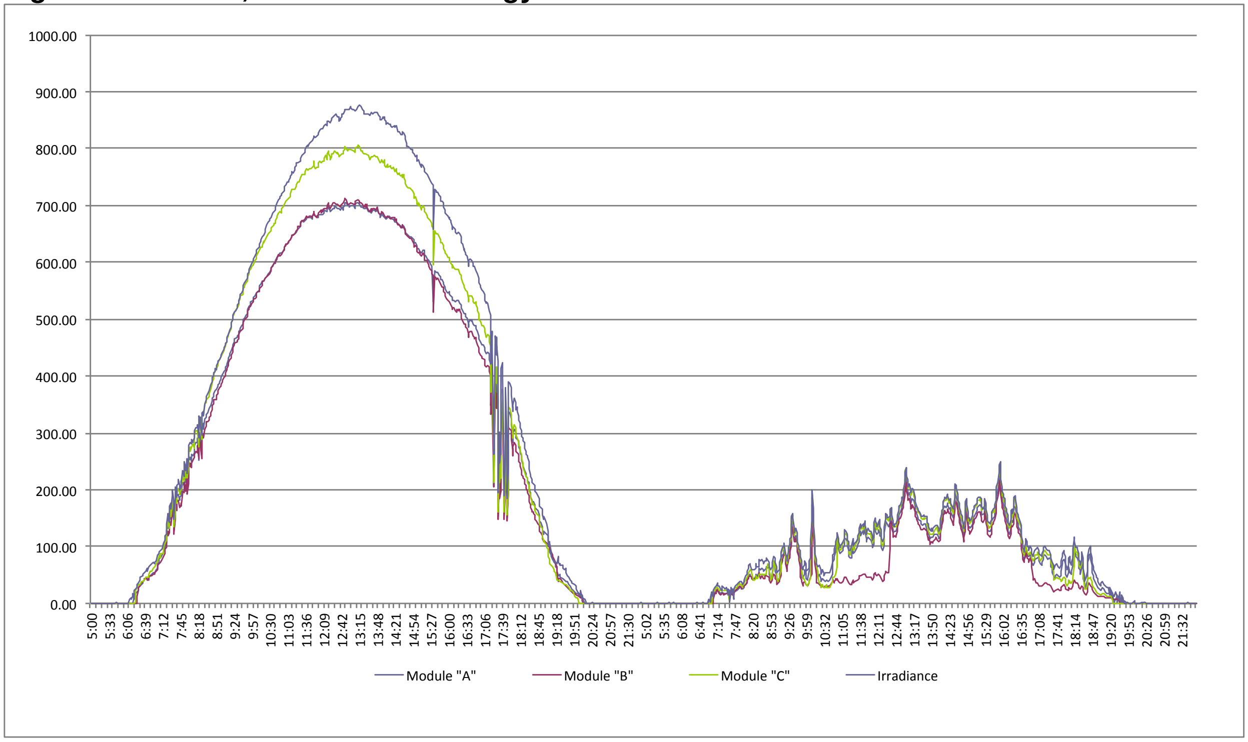
Table 2: Test Array Data & Analysis -

	Date	Time	DC W	DC V	DC A	IRR W/m2	°C	Calculated PWR	(Act /Calc)
A	25/05/2012	8:00	300.19	188.8	1.59	302	4.5	328.62	91.35%
	25/05/2012	8:01	355.70	189.2	1.88	339	5.3	367.72	96.73%
	25/05/2012	8:02	435.71	191.1	2.28	424	6.5	457.73	95.19%
	25/05/2012	8:03	312.79	187.3	1.67	305	7.3	328.21	95.30%
	25/05/2012	8:04	192.39	181.5	1.06	187	6.5	201.88	95.30%
	25/05/2012	8:05	187.72	180.5	1.04	183	5.9	198.03	94.79%
	26/05/2012	16:50	755.42	184.7	4.09	705	14.9	735.62	102.69%
	26/05/2012	16:51	723.78	183.7	3.94	679	16.2	704.69	102.71%
	26/05/2012	16:52	689.16	182.8	3.77	647	17.4	668.14	103.14%
	26/05/2012	16:53	655.18	182.5	3.59	614	18.1	632.22	103.63%
	26/05/2012	16:54	627.21	181.8	3.45	586	18.9	601.37	104.30%
	26/05/2012	16:55	606.88	181.7	3.34	566	18.9	580.85	104.48%
B	25/05/2012	8:00	282.42	371.6	0.76	302	2.2	319.67	88.35%
	25/05/2012	8:01	330.62	375.7	0.88	339	2.9	357.81	92.40%
	25/05/2012	8:02	409.64	379.3	1.08	424	4.1	445.32	91.99%
	25/05/2012	8:03	293.76	367.2	0.8	305	4.6	319.68	91.89%
	25/05/2012	8:04	180.80	354.5	0.51	187	3.4	196.97	91.79%
	25/05/2012	8:05	177.85	355.7	0.5	183	2.7	193.31	92.00%
	26/05/2012	16:50	744.02	379.6	1.96	705	12.2	715.78	103.94%
	26/05/2012	16:51	708.38	376.8	1.88	679	13.5	685.57	103.33%
	26/05/2012	16:52	674.82	374.9	1.8	647	14.4	650.75	103.70%
	26/05/2012	16:53	634.95	373.5	1.7	614	14.6	617.03	102.90%
	26/05/2012	16:54	606.36	372	1.63	586	14.7	588.63	103.01%
	26/05/2012	16:55	587.13	371.6	1.58	566	14.6	568.79	103.22%
C	25/05/2012	8:00	312.29	321.95	0.97	302	0.9	345.11	90.49%
	25/05/2012	8:01	366.91	324.7	1.13	339	1.6	386.38	94.96%
	25/05/2012	8:02	452.93	325.85	1.39	424	2.4	481.82	94.00%
	25/05/2012	8:03	321.99	318.8	1.01	305	3.1	345.68	93.15%
	25/05/2012	8:04	199.78	312.15	0.64	187	3	212.02	94.22%
	25/05/2012	8:05	196.31	311.6	0.63	183	2.6	207.80	94.47%
	26/05/2012	16:50	854.53	320.05	2.67	705	13.2	768.67	111.17%
	26/05/2012	16:51	819.06	318.7	2.57	679	14.8	735.69	111.33%
	26/05/2012	16:52	777.26	317.25	2.45	647	15.7	698.54	111.27%
	26/05/2012	16:53	737.21	316.4	2.33	614	16.6	660.55	111.61%
	26/05/2012	16:54	705.01	316.15	2.23	586	16.6	630.43	111.83%
	26/05/2012	16:55	680.94	315.25	2.16	566	16.8	608.43	111.92%

Energy Production -

Figure 1 illustrates the production performance of the three technologies against the irradiance for the Carlisle test array. The first day (on the left) shows performance on a clear, sunny day. The second day (on the right) shows performance on a cloudy day with intermittent sun.

Figure 1: Carlisle, PA Test Site Energy Production



The second consideration is the energy produced by each array. CCM compared the array data from each site to see which manufacturer produced the most energy. The team also converted the energy output to yield using the nameplate rating of each module. At first glance, Module "C" seems to have the best energy yield. In Nevada, where the sunlight resource and red light is high and the temperature relatively low in the mornings, it has a 10% advantage over Module ”A" and "B." However, in Washington and Pennsylvania, where there is less light resource and more cloud cover and blue light, this advantage is reduced to ~%5. This data was to be collected and compared over one year to determine which technology has the best output in all climates and seasons

Table 3: Total Production of the Test Arrays -

	Module "A" (1000W)				Module "B" (976W)				Module "C" (1040W)			
Site	Start	End	Total kWh	kWh/ kW	Start	End	Total kWh	kWh/ kW	Start	End	Total kWh	kWh/ kW
Location 3	152.2	373.4	221.2	221.2	123.1	343.7	220.6	226.02	144.8	400.8	256	246.15
Location 2	77.7	213.2	135.5	135.5	77	211.2	134.2	137.50	111.9	260.9	149	143.27
Location 4	100	311	211	211	97.4	300.9	203.5	208.50	109	341.4	232.4	223.46
Location 5	12.9	154.5	141.6	141.6	12.5	146.8	134.3	137.60	14.9	179.3	164.4	158.08
Location 1	84.6	246.1	161.5	161.5	83	202.4	119.4	122.34	92.1	269.7	177.6	170.77

Defective module replaced during test period

Proof of Concept

Finally, in order to demonstrate a proof concept for this project, prototype modules were manufactured in a large format using both technology A and B flexible CIGS modules. CCM successfully laminated these PV modules onto Carlisle's Thermoplastic Olefin (TPO) commercial roof membrane utilizing the custom lamination machine created for this project by Spaleck-Stevens InnoTech, GmbH.

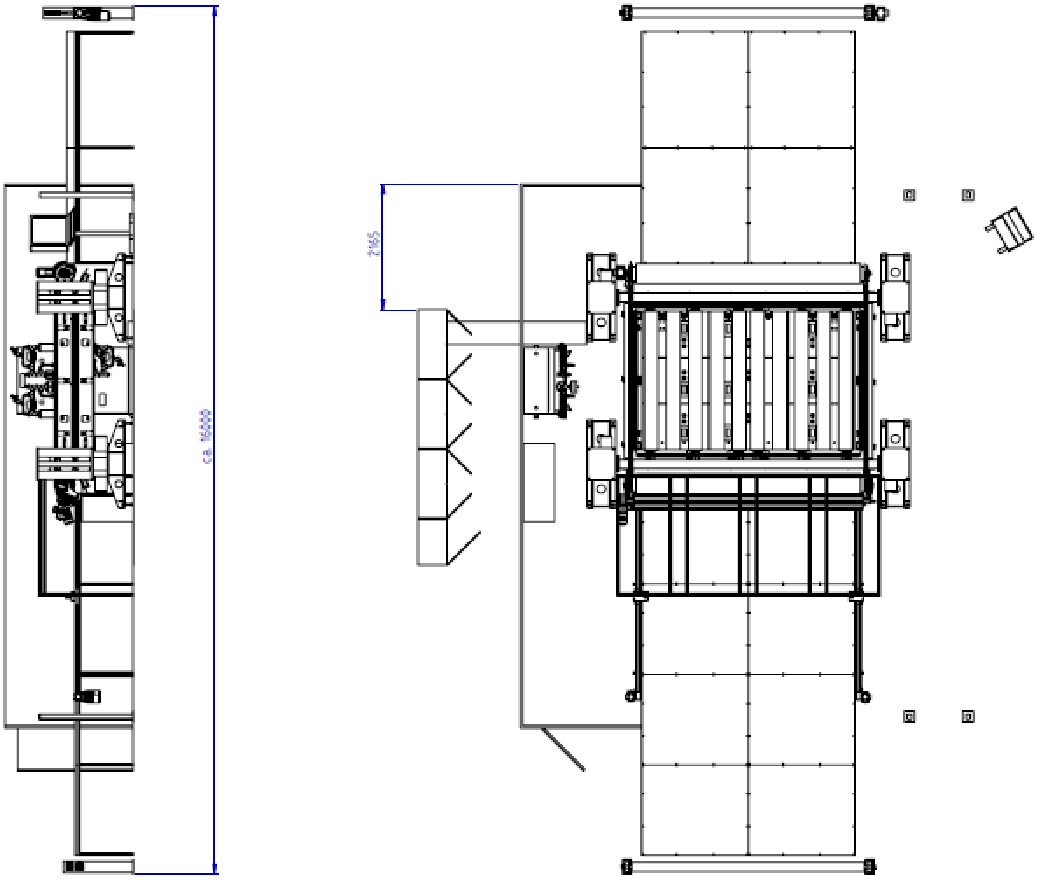
A 12' wide by 7.5' long unit as a series of smaller units on one roll has been developed to allow for modularity to avoid roof obstacles as well as to maximize material usage from a cost perspective. Using this form factor, three sample units were created during the factory acceptance test the week of July 9, 2012 in Bocholt, Germany. They have been shipped back to the U.S. for CTE, adhesion, and other preliminary roofing acceptance tests. Images of the sample are shown in Figures 2 and 3.

Figure 2: Prototype Module

Task 2: Procure Laminator and Associated Equipment

During the first phase of this project, CCM procured a custom lamination machine in order to create prototype Building Integrated Photovoltaic (BIPV) roof membranes for testing and evaluation. The process for procuring the laminator involved the development of engineering specifications in conjunction with vendor evaluations. Internally, both an Application for Capital Expense (ACE) and a Pre-Approval Process were successfully executed. The ACE required the submission of an internal Carlisle justification and budget for capital expenditure. The ACE was reviewed and approved by the Director of R&D, the Vice Presidents of Engineering, Operations, Sales and Marketing, and the President of CCM. Further, CCM submitted the procurement of the laminator to the DOE for pre-approval. This process took approximately six weeks. Concerns from the DOE were raised regarding the Coefficient of Thermal Expansion (CTE) mismatch among material layers. As a result, the scope of this project was expanded to include a Finite Element Analysis (FEA) to identify compatibility of the different materials in the BIPV product and their interaction on a very large format. This objective fits well within the scope of the program. Test results for CTE experiments can be found in Figure 7 on page sixteen (16).

Figure 3: Laminator Illustration -



In addition to the procurement of the laminator, a winder/unwinder mechanism was identified as a necessary component of the lamination line. A Wisconsin-based company named Webex, Inc. was identified to collaborate with Spaleck-Stevens to design, engineer, construct and deliver the lamination line.

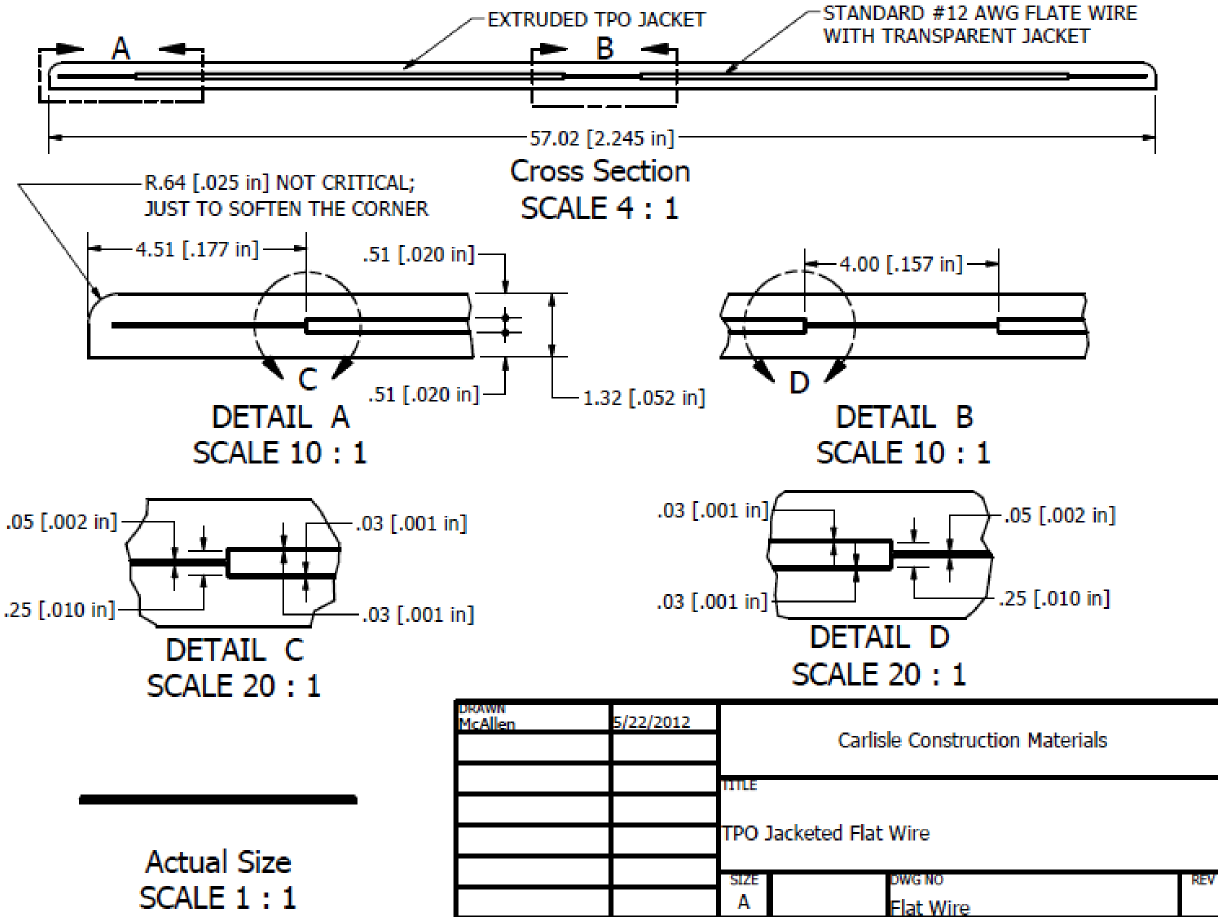
Further, CCM brought together resources from internal Engineering, Mechanical, Construction departments as well as Electrical consultants to work closely with Spaleck-Stevens and Webex to execute this project. Space in Carlisle's Annex facility was designated and modified to accommodate the lamination line. These modifications include updates to the air conditioning, electrical, and compressed air capacity, as well as a closing off a section of the annex to prevent infiltration of unwanted pollutants that could be counterproductive to the manufacturing process.

Side View of the Lamination Line

Task 3: Design Junction Box and Associated Electrical Components -

In conjunction with the form factor design, CCM developed designs for the junction box and associated electrical component design. Please see Figure 5 on the following page for a conceptual design for the junction box and associated electrical components.

Figure 4: Conceptual Design of TPO Jacketed Wire Scheme -

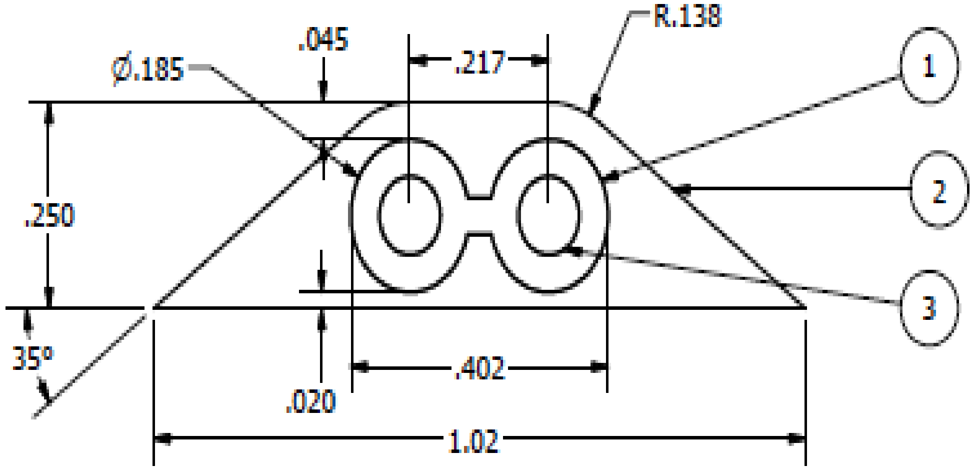


In this process, CCM identified potential wiring and junction box suppliers. Specifically, Southwire had been identified as the potential provider of a flatwire solution to be incorporated into the form factor during the lamination process. This design solution provided a low profile DC wiring application that can work with CCM's BIPV design to handle voltage and transportation requirements.

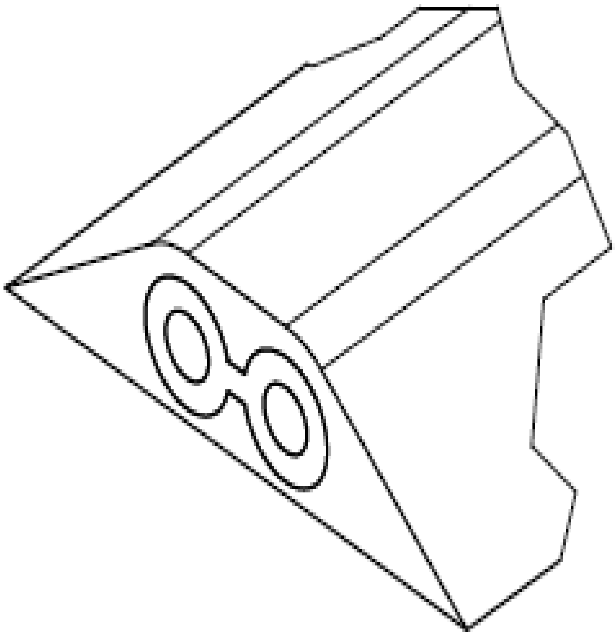
For this project a customized junction box, wiring scheme and wire trace would need to be developed. CCM has developed the design in Figure 6 for the wire trace.

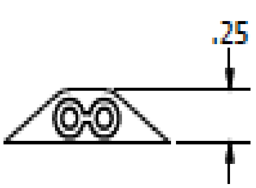
During this process CCM evaluated different methods for attaching the wire trace to the roof membrane evaluating adhesives, heat welding and sonic soldering techniques. While adhesives and heat welding are well-known techniques for roof applications, sonic welding was tested under lab conditions. However, this technique did not provide the necessary adhesion required for a twenty year life cycle.

Figure 5: Conceptual Design for Wire Trace -

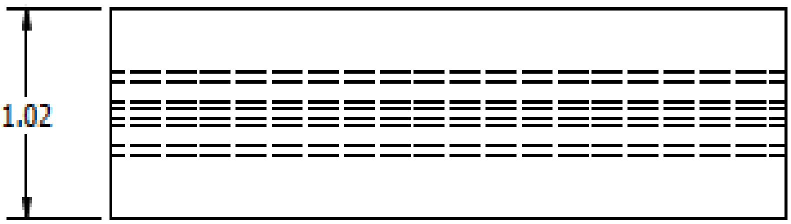


Cross Section
SCALE 4 : 1





Actual Size
SCALE 1 : 1



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Task 4: Perform Initial Qualifying Evaluation -

During the first phase of the project, CCM conducted a number of internal and external lab tests in order to identify failure modes for the various components of the BIPV product assembly. Further, testing was conducted to characterize prototype modules and determine the best combination of cell and encapsulation technologies.

In order to determine what testing methods, evaluation procedures and failure modes the following set of testing tools were created:

1. Design of Experiments (DOE) – The following DOE organized three separate sets of experimental trials needed for the evaluation of Adhesion, Coefficient of Thermal Expansion (CTE) mismatch, Power output, Xenon Arc, and Weatherability through a battery of contemplated formulations as well subsequent use for a potential BIPV product.

2. Performance Critical to Quality (CTQ) Matrix – The CTQ in Part 1: Attachment B establishes a comprehensive set of specific and measurable criteria and the associated testing and expected outcomes essential for commercial roofing membranes in conjunction with a BIPV product. These values provide a guideline for testing the most important criteria associated with this product.

3. Vital to driving down the cost of a fully integrated BIPV product is the elimination of redundant materials and processing steps. By significantly reducing the water vapor transmission rate (*WVTR*) of the TPO membrane, it may be possible to eliminate the traditional fluoropolymer-based backsheet currently used in flexible modules, while at the same time encapsulating all the module materials together in one lamination step. In order to achieve very low water vapor transmission, different additives were mixed into the standard TPO formulation. The intention was to create a more tortuous path through the TPO membrane to slow the transmission of water vapor. In Sample 1, an order of magnitude better WVTR was achieved. The additives used in this sample were standard grade, with no particularly advanced properties, but it is believed that by mixing the same formulation with specially selected additives, the WVTR may be lowered even further. More research is required to identify potential formulation changes that can improve this property.

Table 3: Approach 1-BIPV –

	Adhesive	Surface Treatment	Characteristic	Test	Where
Trial 1a Small Module to TPO	Adhesive 1	None	Adhesion, CTE Mismatch, Weatherability	ASTM D 751 for adhesion, ASTM D 696 for CLTE, Freeze Thaw Cycling (-40°C to 90°C), Damp heat exposure, Xenon Arc Weathering	Location 1-4
Trial 1b Small Module to TPO	Adhesive 1	Primer*	Adhesion, CTE Mismatch, Weatherability	ASTM D 751 for adhesion, ASTM D 696 for CLTE, Freeze Thaw Cycling (-40°C to 90°C), Damp heat exposure, Xenon Arc Weathering	Location 1-4
Trial 1c Small Module to TPO	Adhesive 1	Ozone*	Adhesion, CTE Mismatch, Weatherability	ASTM D 751 for adhesion, ASTM D 696 for CLTE, Freeze Thaw Cycling (-40°C to 90°C), Damp heat exposure, Xenon Arc Weathering	Location 1-4
Trial 1d Small Module to TPO	Adhesive 1	Plasma*	Adhesion, CTE Mismatch, Weatherability	ASTM D 751 for adhesion, ASTM D 696 for CLTE, Freeze Thaw Cycling (-40°C to 90°C), Damp heat exposure, Xenon Arc Weathering	Location 1-4
Trial 2a Small Module to TPO	Adhesive 2	None	Adhesion, CTE Mismatch, Weatherability	ASTM D 751 for adhesion, ASTM D 696 for CLTE, Freeze Thaw Cycling (-40°C to 90°C), Damp heat exposure, Xenon Arc Weathering	Location 1-4
Trial 2b Small Module to TPO	Adhesive 2	Primer*	Adhesion, CTE Mismatch, Weatherability	ASTM D 751 for adhesion, ASTM D 696 for CLTE, Freeze Thaw Cycling (-40°C to 90°C), Damp heat exposure, Xenon Arc Weathering	Location 1-4
Trial 2c Small Module to TPO	Adhesive 2	Ozone*	Adhesion, CTE Mismatch, Weatherability	ASTM D 751 for adhesion, ASTM D 696 for CLTE, Freeze Thaw Cycling (-40°C to 90°C), Damp heat exposure, Xenon Arc Weathering	Location 1-4
Trial 2d Small Module to TPO	Adhesive 2	Plasma*	Adhesion, CTE Mismatch, Weatherability	ASTM D 751 for adhesion, ASTM D 696 for CLTE, Freeze Thaw Cycling (-40°C to 90°C), Damp heat exposure, Xenon Arc Weathering	Location 1-4
Trial 3a Small Module to TPO	DOW PO	None	Adhesion, CTE Mismatch, Weatherability	ASTM D 751 for adhesion, ASTM D 696 for CLTE, Freeze Thaw Cycling (-40°C to 90°C), Damp heat exposure, Xenon Arc Weathering	Location 1-4
Trial 3b Small Module to TPO	Adhesive 1	Primer*	Adhesion, CTE Mismatch, Weatherability	ASTM D 751 for adhesion, ASTM D 696 for CLTE, Freeze Thaw Cycling (-40°C to 90°C), Damp heat exposure, Xenon Arc Weathering	Location 1-4
Trial 3c Small Module to TPO	Adhesive 1	Ozone*	Adhesion, CTE Mismatch, Weatherability	ASTM D 751 for adhesion, ASTM D 696 for CLTE, Freeze Thaw Cycling (-40°C to 90°C), Damp heat exposure, Xenon Arc Weathering	Location 1-4
Trial 3d Small Module to TPO	Adhesive 1	Plasma*	Adhesion, CTE Mismatch, Weatherability	ASTM D 751 for adhesion, ASTM D 696 for CLTE, Freeze Thaw Cycling (-40°C to 90°C), Damp heat exposure, Xenon Arc Weathering	Location 1-4
Trial 4a Large Module to TPO	Downselected PO Adhesive	None	Adhesion, CTE Mismatch, Weatherability	ASTM D 751 for adhesion, ASTM D 696 for CLTE, Freeze Thaw Cycling (-40°C to 90°C), Damp heat exposure, Xenon Arc Weathering	Location 1-4
Trial 4b Large Module to TPO	Downselected PO Adhesive	Primer*	Adhesion, CTE Mismatch, Weatherability	ASTM D 751 for adhesion, ASTM D 696 for CLTE, Freeze Thaw Cycling (-40°C to 90°C), Damp heat exposure, Xenon Arc Weathering	Location 1-4
Trial 4c Large Module to TPO	Downselected PO Adhesive	Ozone*	Adhesion, CTE Mismatch, Weatherability	ASTM D 751 for adhesion, ASTM D 696 for CLTE, Freeze Thaw Cycling (-40°C to 90°C), Damp heat exposure, Xenon Arc Weathering	Location 1-4
Trial 4d Large Module to TPO	Downselected PO Adhesive	Plasma*	Adhesion, CTE Mismatch, Weatherability	ASTM D 751 for adhesion, ASTM D 696 for CLTE, Freeze Thaw Cycling (-40°C to 90°C), Damp heat exposure, Xenon Arc Weathering	Location 1-4

Table 4: Approach 2 - BIPV Stack -

		Technology A	B	C	Characteristic	Test	Test Location	# Samples
Trial 1	Topsheet	Top Sheet 1		Top Sheet 2	Adhesion, CTE Mismatch, Power Output	ASTM D 751, Freeze-Thaw Cycling (-40°C to 90°C), Efficiency over time during damp heat exposure	Loc. 1-4	6 (2 ea. cell mfg.)
	Encapsulant	Encapsulatant 1		Encapsulant 1				
	Edge Seal	Edge Seal 1		N/A				
	WVB/Backsheet	Backsheet 1		TPO				
Trial 2	Topsheet	Top Sheet 1		Top Sheet 2	Adhesion, CTE Mismatch, Power Output	ASTM D 751, Freeze-Thaw Cycling (-40°C to 90°C), Efficiency over time during damp heat exposure	Loc. 1-4	6 (2 ea. cell mfg.)
	Encapsulant	Encapsulatant 1		Encapsulant 1				
	Edge Seal	Edge Seal 1		N/A				
	WVB/Backsheet	Backsheet 1		TPO				
Trial 3	Topsheet	Top Sheet 1		Top Sheet 2	Adhesion, CTE Mismatch, Power Output	ASTM D 751, Freeze-Thaw Cycling (-40°C to 90°C), Efficiency over time during damp heat exposure	Loc. 1-4	6 (2 ea. cell mfg.)
	Encapsulant	Encapsulatant 2		Encapsulant 2				
	Edge Seal	Edge Seal 1		N/A				
	WVB/Backsheet	Backsheet 2		TPO				
Trial 4	Topsheet	Top Sheet 3		Top Sheet 4	Adhesion, CTE Mismatch, Power Output	ASTM D 751, Freeze-Thaw Cycling (-40°C to 90°C), Efficiency over time during damp heat exposure	Loc. 1-4	6 (2 ea. cell mfg.)
	Encapsulant	Encapsulatant 2		Encapsulant 2				
	Edge Seal	Edge Seal 1		N/A				
	WVB/Backsheet	Backsheet 2		TPO				
Trial 5	Topsheet	Top Sheet 3		Top Sheet 4	Adhesion, CTE Mismatch, Power Output	ASTM D 751, Freeze-Thaw Cycling (-40°C to 90°C), Efficiency over time during damp heat exposure	Loc. 1-4	6 (2 ea. cell mfg.)
	Encapsulant	Encapsulatant 2		Encapsulant 2				
	Edge Seal	Edge Seal 1		N/A				
	WVB/Backsheet	Backsheet 2		TPO				
Trial 6	Topsheet	Top Sheet 3		Top Sheet 5	Adhesion, CTE Mismatch Power Output	ASTM D 751, Freeze-Thaw Cycling (-40°C to 90°C), Efficiency over time during damp heat exposure	Loc. 1-4	6 (2 ea. cell mfg.)
	Encapsulant	Encapsulatant 3		Encapsulant 3				
	Edge Seal	Edge Seal 1		N/A				
	WVB/Backsheet	Backsheet 2		TPO				

Table 5a: Individual Component Testing –

		Formulation	Characteristic*	Test	Where
Trial 1	Low WVTR TPO	Std Control	Adhesion, WVTR	ASTM D 751, ASTM F 1249	Carlisle, Test lab
Trial 2	Low WVTR TPO	Formulation 1	Adhesion, WVTR	ASTM D 751, ASTM F 1249	Carlisle, Test lab
Trial 3	Low WVTR TPO	Formulation 2	Adhesion, WVTR	ASTM D 751, ASTM F 1249	Carlisle, Test lab
Trial 4	Low WVTR TPO	Formulation 3	Adhesion, WVTR	ASTM D 751, ASTM F 1249	Carlisle, Test lab
Trial 5	Low WVTR TPO	Formulation 4	Adhesion, WVTR	ASTM D 751, ASTM F 1249	Carlisle, Test lab
Trial 6	Low WVTR TPO	Formulation 5	Adhesion, WVTR	ASTM D 751, ASTM F 1249	Carlisle, Test lab
Trial 7	Low WVTR TPO	Formulation 6	Adhesion, WVTR	ASTM D 751, ASTM F 1249	Carlisle, Test lab
Trial 8	Low WVTR TPO	Formulation 7	Adhesion, WVTR	ASTM D 751, ASTM F 1249	Carlisle, Test lab
Trial 9	Low WVTR TPO	Formulation 8	Adhesion, WVTR	ASTM D 751, ASTM F 1249	Carlisle, Test lab

**Other characteristics related to using the TPO as a roofing material were considered before beginning WVTR or adhesion testing , including tensile strength (psi), tearing strength (ppi), thickness (mils), color (L*a*,b*), hardness (Shore A), and Xenon arc testing (# hours, 10x microscope with no cracks).*

Table 5b: Individual Component Testing -

	Formulation	Characteristic	Test	Where
Trial 1 WVB/Backsheet	Backsheet TAPE 1/ Std TPO	Interlayer Adhesion, WVTR	ASTM D 751, ISO 1506-3	Carlisle, Test Lab
Trial 2 WVB/Backsheet	Foil 1/Std TPO	Interlayer Adhesion, WVTR	ASTM D 751, ISO 1506-3	Carlisle, Test Lab
Trial 3 WVB/Backsheet	TAPE 2	Interply Adhesion, WVTR	ASTM D 751, ISO 1506-3	Carlisle, Test Lab
Trial 4 WVB/Backsheet	Foil 2	Interply Adhesion, WVTR	ASTM D 751, ISO 1506-3	Carlisle, Test Lab
Trial 5 WVB/Backsheet	Backsheet 2/Enhanced TPO	Interlayer Adhesion, WVTR	ASTM D 751, ISO 1506-3	Carlisle, Test Lab
Trial 6 WVB/Backsheet	Backsheet 1/Enhanced TPO	Interlayer Adhesion, WVTR	ASTM D 751, ISO 1506-3	Carlisle, Test Lab

Table 6 below illustrates the water vapor transmission rate (WVTR) results from 10 different TPO formulations, including two control samples.

Table 6: Water Vapor Transmission Rate Results -

Sample	WVTR (g/m2/day)
1	0.0208
2	0.167
3	0.233
4	0.269
5	0.171
6	0.117
7	0.195
8	0.250
9	0.132
10 - Control (55 mil TPO non-reinforced)	0.240
11 - Control (60 mil TPO reinforced)	0.191
12 – Foil water vapor barrier	0.00055

A critical factor in integrating flexible modules to a roof membrane is adhesion. Testing showed that, compared to a baseline control for Carlisle SecurTape adhesive (currently used in Generation 1 Carlisle PowerMat), very good adhesion was found with the DuPont polyolefin. Other polyolefin adhesive films that are to be investigated include those from 3M and Dow. As shown in the design of experiments document, the adhesive layers will be subjected to different environmental conditions to further validate adhesion.

Table 7 lists the adhesion testing results for a commercially available polyolefin adhesive bonding TPO and backsheet materials. These test results are based on small-scale lab samples. The test methods used to determine peel strength are as per standard roofing industry practices.

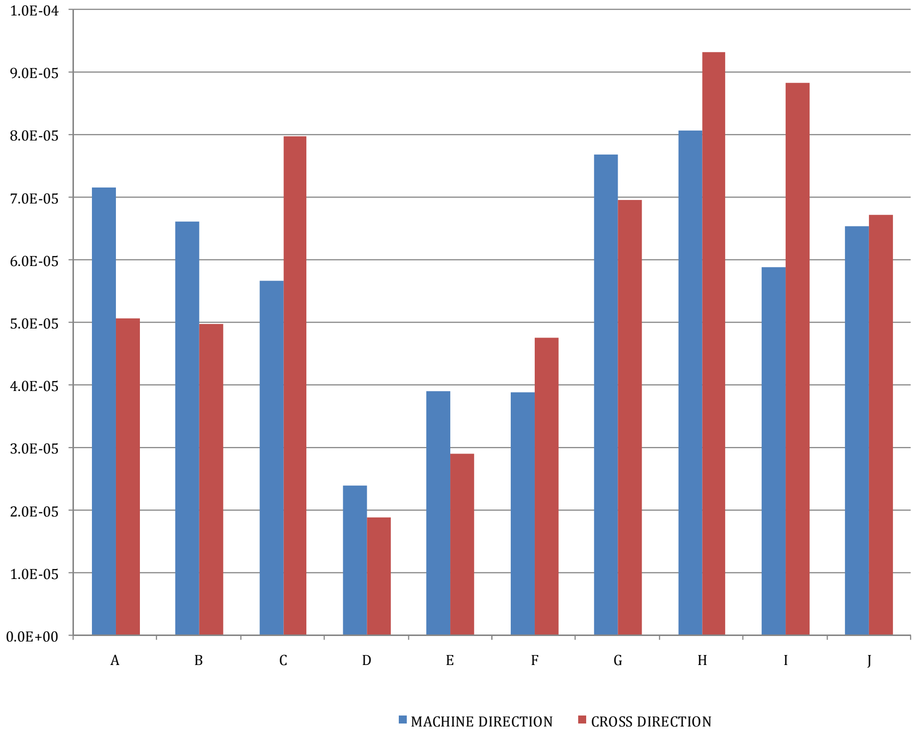
Table 7: Adhesion Testing Results -

Material	Peel Strength, in pounds-force per linear inch (pli)	Adhesive
TPO to Backsheet 1	19.8	Adhesive 1
TPO to Backsheet 2	22.4	Adhesive 1
TPO to Tape 1	11.8	Control Tape

As an extension of the adhesion testing of the module materials, studies will be performed to investigate coefficient of thermal expansion compatibility among material layers. A baseline study of TPO materials has been performed by CCM, with the results shown in Table 7. Different formulations of TPO could be used to be best compatible with the CTE of the module materials.

Figure 7 below depicts the CLTE of different TPO formulations in the machine direction and cross direction of the material.

Figure 6: CLTE of Different TPO Formulations -



Material procurement was a challenge in making more advanced progress in testing. A significant portion of the testing plans would have continued into Year 2 for a thorough validation and down-selection of materials.