Development of a Modular Solar Shingle

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Development of a Modular Solar Shingle

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Final Report for MECE:497 Senior/Honors Design, Spring 2024

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Abstract

The goal of this research project is to design, prototype, and test an array of solar roofing shingles using print-in-place principles using an automated circuitry printer and 3D printed components. The shingle shall emphasize ease of installation, maintenance, and affordability in contrast to the current market for solar roofing. The design goal is to develop a manufacturing process to be more cost and time effective than current manufacturing techniques. The prototype will consist of a roof with this system, demonstrating the durability, assembly, and ease of installation. Finally, material/design suitability will be implemented in conjunction with post-processing techniques to create a fair comparison to current market competitors in solar power generation.
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1 Introduction and Objectives

The objective of the project has two levels. First, the market for solar roofing, or solar power on a commercial level in general, is very expensive and not currently accessible to the general population. According to a blog published on roofgnome.com, a solar roofing system typically costs from $40,000-60,000, averaging $49,700. For many people, investing in solar roofing can be difficult to rationalize. Reducing this cost using innovative manufacturing techniques could greatly increase the number of consumers looking to move to renewable energy, including solar power. Secondly, according to the Solar Energy Industries Association, solar energy is the cleanest form of energy that is readily available (About Solar Energy), especially as natural gas and oil accounted for over 59% of electricity generated in the United States in 2022 (EIA). Solar roofing also requires minimal upkeep when functioning properly. Reducing up-front costs associated with solar energy could help in creating a cleaner world for ourselves and future generations.
2 Modular Shell Design

2.1.1 Additive Manufacturing

3D printing and automated circuitry printing is being utilized to manufacture the shingles. The use of these printing methods allows us to modify designs rapidly to adjust to changes in materials and processes; Further, it also limits the labor required to produce a unit. We also demonstrated the ability to print our circuitry directly onto 3D printed substrates. This will be done using the Voltera Nova circuitry printer, along with testing and validation on the Voltera V-One printer.

2.1.2 Economics and Availability of 3D Printing

3D printers have greatly reduced in price over the past decade and now can be easily purchased and utilized by hobbyists and small machine shops. The filament is relatively inexpensive, does not require costly injection-molding techniques, and the power draw is low compared to traditional machining tools. The 3D printer is what allows these normally hard to manufacture solar shingles to be manufactured by small scale operations and individuals rather than only well-established manufacturers.

2.1.3 Mechanical Connections

Inspiration was taken from vinyl flooring for the shingle-to-shingle connections. Multiple iterations were developed, lipped edges, slide-in connections, and hinge connections. The goal was to allow a shingle to be electrically connected to the surrounding cells without wiring and be able to easily swap cells in and out individually.
2.1.4 Iterative Mechanical Design

The initial design was a modular solar shingle that could be electrically connected in series and linked together to form a full array of shingles. The initial sketch alongside our calculations for the shingle power output estimations.
First Design Sketch – 9/15/2023

From this, we decided on designing the solar shingle as a 3D printed container that would encase a solar cell. We started by exploring different possibilities for what the shingle-to-shingle electrical connection would look like and how we would construct the 3D printed envelope around these electrical connectors. The decision to hold off on designing the roof mounting system at that time was made to allow for flexibility in designing the shingle to all the other more restrictive design requirements.

The design path landed upon was a two-part shingle. The bottom part would be a 3D printed rectangular plate that we would then print the circuitry onto as denoted by 1 in the sketch. This circuitry would have electrically conductive pads that we could solder the electrical
connectors onto and solder the solar cell onto. The top part would be a 3D printed shell that would have a clear polycarbonate lid and side holes to fit the electrical connectors as denoted by 4 in the sketch.

**Brainstorming Design Sketch 1 – 10/18/2023**

![Brainstorming Design Sketch 1](image)

*Figure 3: Conceptual Design Sketch: Modularity*

The drawing denoted by 2 in the sketch is our idea of what the electrical connector would possibly look like so that it would be able to be soldered. The 3rd and 10th drawings came about as a realization that the 3D printer would not be able to print wall sections right next to the electrical connectors as the 3D printer’s nozzle would crash into the electrical components. The 5th and 9th drawings were used for brainstorming how the electrical connectors would be configured in the solar shingle. The 5th drawing was for the electrical connector pads connecting
as they slide past each other and the 9th drawing for the connectors being soldered to wires and connected externally from the shingle. The 6th and 8th drawings were for exploring how the shingles could be mounted to the roof through horizontal rails that the shingle would be secured to with screws. The 7th and 11th drawing were used to decide what design direction to move forward in. We chose between having the shingle be 2 parts with the circuitry printed directly onto the bottom 3D printed plate, having the shingle be a complete 3D printed box that we later insert a completed circuit board into, or printing the bottom plate, then printing the circuitry, and then finally printing the walls around that circuitry to finish the shingle. Ultimately, the decision was made to continue the design phase using a two-part assembly.

**Brainstorming Design Sketch 2 – 10/18/2023**

![Figure 4: Conceptual Design Sketch 2](image)
Brainstorming Design Sketch 3 – 10/18/2023

Figure 5: Conceptual Design Sketch 3

The search for the ideal electrical connector for our modular design continued. We explored having the shingles slide past each other and connecting using leaf spring connectors designed for PCB’s.

Electrical Connector Solution 1 – 11/3/2023

Figure 6: Leaf Spring Connector Proposal
After purchasing and further examining the connector, it was noted that soldering these connectors in the required orientation would prove difficult and lack mechanical strength. We then moved forward with exploring other options that could more easily be soldered into place. We found several possible solutions that ended up being nonviable due to sizing constraints and extensive lead times.

**Electrical Connector Solution 2 – 1/24/2024**

![POGO Electrical Connector Proposal](image)

*Figure 7: POGO Electrical Connector Proposal*

As the search for a viable electrical connector continued, we moved forward with the detailed design for the modular connections. We created sketches of what the interfacing surfaces would look like for the top and bottom parts and how they would create a sliding connection from shingle to shingle. The curved surface along the smaller faces of the shingle is to guide each shingle into its position in the array alongside the other shingles and to guide water away from the electrical connections. The indentation in the bottom plate is for aligning the top and bottom halves for a proper fit.
Following initial sketches, the first SolidWorks model iteration was created, labeled Type A. The assembly includes the indented bottom plate (green) with attached circuitry (yellow), the top shell (black), the solar cell (blue), and the polycarbonate pane (clear). When deciding what filament, we wanted the prototype to be 3D printed in, the Ohio Administrative Code Rule 4101:1-15-01 | Roof assemblies and rooftop structures was followed. Specifically, Section 1505.9 Photovoltaic panels and modules that states “Rooftop mounted photovoltaic panel systems shall be tested, listed and identified with a fire classification in accordance with UL 1703.”

The search was narrowed for filaments that have passed both the Spread of Flame and Burning Brand on Top of Surface tests in accordance with UL 1703. ASA filament was selected because, along with its accordance with UL 1703, it had a high enough melting temperature to be able to withstand the curing temperature for the printed electrical traces and soldering temperatures for the electrical components.
Type A SolidWorks Assembly – 1/15/2024

Figure 9: SolidWorks Assembly (Type A)
Once we selected an electrical connector, we began discussing how the model would be adjusted to accommodate this magnetic electrical connector.

**Final Electrical Connector Solution – 1/30/2024**
When integrating this into the design, the curved grooves would need to be widened to account for the geometry of the electrical connectors. If this was not done, a partial connection or an inability to slot the shingles into each other to form an array was encountered.

**Electrical Connector Interference Drawing – 1/30/2024**

![Image of Electrical Connector Interference Drawing]

*Figure 12: Electrical Connector Interference fit*

We decided to change out the curved grooves for a groove with flatter surfaces and moved forward with measuring out and modeling the electrical connectors. This design change was made, as having the grooves consist of flat surfaces made iterating and dimensioning the design easier to reproduce. We then began modeling a new iteration, labelled Type B.
Sketch of Dimensioned Type B – 1/30/2024

Figure 13: Nested Electrical Connector Sketch (Type B)

Type B SolidWorks Demonstration Assembly – 1/30/2024

Figure 14: Type B SolidWorks Interlocking Assembly
After the initial rough modeling, Type B was finalized by modifying the tolerances of the bottom plate for better fit and modified the top half for electrical connector tolerancing concerns.

**Type B SolidWorks Assembly – 2/6/2024**

![SolidWorks Type B Assembly with Nested Connector](image)

*Figure 15: SolidWorks Type B Assembly with Nested Connector*

A lip was added to the inside surface of the top shell to be able to interface with the bottom plate at the correct height and this new model was labelled, Type C.
Figure 16: Type C SolidWorks Assembly

Figure 17: Type C SolidWorks Assembly Cross Section
We then decided to change the design to more easily facilitate the attachment of the bottom and top halves without damaging or bending the electrical connectors off the solder pads. We further integrated the electrical connectors into the bottom and top halves by creating an indent that fits around the connectors more securely. This is more reliable to manufacture during the soldering process, but also proved to be a more robust and stable construction as it indexes the two halves together. We labelled this new iteration Type D.
After printing and checking tolerances, the electrical connector hole sizes were modified. We also changed the shingle-to-shingle lip overhang tolerances as the shingles were not able to properly interface with their neighboring shingles.
We then made another adjustment by decreasing the electrical connector hole size to account for warping during the printing process and the conductive trace cure. We also added a gasket ring between the polycarbonate pane and the solar cell to prevent any movement of the solar cell in the container that could cause the electrical connection to fail.
Final Type D Assembly – 2/28/2024

Figure 21: Final Type D Assembly: Exploded View

Figure 22: Final Type D SolidWorks Assembly
### 2.1.5 Materials

The shingle shell materials includes the 3D printed filament, the polycarbonate (PC) top plate, and sealants or gaskets. For the 3D printed filament, we selected ASA (Acrylonitrile Styrene Acrylate) filament for our design for its UV resistance, high temp. resistance, printability, and vapor smoothing capabilities. We are elected for polycarbonate panels for the weatherproof top plate to protect the electronics while still allowing UV-A and UV-B light through. PC was also selected for its ease of use and ability to be cut using on-campus resources. When selecting the sealants and gaskets that may be required between the polycarbonate and ASA interface, we considered the strength, UV resistance, temperature resistance, and its weatherproofing capabilities. Construction-grade silicone sealant was selected for its ease of procurement, and its ability to effectively waterproof the ASA interface. Material specifications for the ASA chassis are included below:

<table>
<thead>
<tr>
<th>Property</th>
<th>Test Method</th>
<th>Typical Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>HCT @ 85 psi</td>
<td>ASTM D4168</td>
<td>1.022 C (191.0 F)</td>
</tr>
<tr>
<td>HCT @ 264 psi</td>
<td>ASTM D4168</td>
<td>1.073 C (208.3 F)</td>
</tr>
<tr>
<td>Tg</td>
<td>ASTM D1160</td>
<td>2.99 (C)</td>
</tr>
<tr>
<td>Mean CTE</td>
<td>ASTM E691</td>
<td>0.0265 ft²/in² (1.05×10^-5 cm²/m)</td>
</tr>
<tr>
<td>Volume Resistivity</td>
<td>ASTM D257</td>
<td>&gt; 6.8×10^14 ohm.cm</td>
</tr>
<tr>
<td>Dielectric Constant</td>
<td>ASTM D150</td>
<td>3.14</td>
</tr>
<tr>
<td>Dielectric Constant</td>
<td>ASTM D150</td>
<td>4.74</td>
</tr>
<tr>
<td>Dissipation Factor</td>
<td>ASTM D150</td>
<td>2.82</td>
</tr>
<tr>
<td>Dissipation Factor</td>
<td>ASTM D150</td>
<td>2.83</td>
</tr>
<tr>
<td>Thermal Conductivity</td>
<td>ASTM E1592</td>
<td>0.1693 W/m/k</td>
</tr>
<tr>
<td>Thermal Conductivity</td>
<td>ASTM E1592</td>
<td>0.0940 Btu/(h·ft·°F)</td>
</tr>
<tr>
<td>Thermal Conductivity</td>
<td>ASTM E1592</td>
<td>0.1922 W/m/k</td>
</tr>
<tr>
<td>Thermal Conductivity</td>
<td>ASTM E1592</td>
<td>0.0530 Btu/(h·ft·°F)</td>
</tr>
<tr>
<td>Thermal Conductivity</td>
<td>ASTM E1592</td>
<td>0.1503 W/m/k</td>
</tr>
<tr>
<td>Thermal Conductivity</td>
<td>ASTM E1592</td>
<td>0.1058 mm²/s</td>
</tr>
<tr>
<td>Thermal Conductivity</td>
<td>ASTM E1592</td>
<td>1.67×10^-4 in²/s</td>
</tr>
<tr>
<td>Thermal Conductivity</td>
<td>ASTM E1592</td>
<td>0.056 mm²/s</td>
</tr>
<tr>
<td>Thermal Conductivity</td>
<td>ASTM E1592</td>
<td>1.38×10^-4 in²/s</td>
</tr>
<tr>
<td>Thermal Conductivity</td>
<td>ASTM E1592</td>
<td>0.077 mm²/s</td>
</tr>
<tr>
<td>Specific Gravity</td>
<td>ASTM D297</td>
<td>1.08</td>
</tr>
</tbody>
</table>

* Testing done on ASA - not a material
The printing specifications for our process were as follows:

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model Infill Percentage</td>
<td>100%</td>
</tr>
<tr>
<td>Printing Speed</td>
<td>100 mm/s</td>
</tr>
<tr>
<td>Supports Required?</td>
<td>N/A</td>
</tr>
<tr>
<td>Adhesion Support?</td>
<td>N/A</td>
</tr>
<tr>
<td>Extruder Temperature</td>
<td>250° C</td>
</tr>
<tr>
<td>Bed Temperature</td>
<td>100° C</td>
</tr>
<tr>
<td>Chamber Temperature</td>
<td>70 °C</td>
</tr>
</tbody>
</table>

Table 1: Stratasys ASA 3D printing specifications

### 2.1.6 Weatherproofing

To prevent the negative impacts of the environment on the shingles, considerations were made in the production and design. The porosity of the printed material is an issue to be
addressed to prevent the absorption of rainwater. This can be prevented through acetone
smoothing. There are also considerations to be made for the UV resistance of the plastic base
material. The design also includes an overhang above all seams between shingles. This allows
for water to run off the shingles without getting entrapped and eroding the material.

2.1.7 Post Processing
As 3D printed parts are layers of adhered material, these layers can leave layer lines. The
creation of these layer lines has several effects. They affect aesthetic appearance, leave grooves
for water to pool, and create stress concentrations within the part. The use of acetone vapor
smoothing as a post processing technique can aid in preventing the above and negate the
performance losses of that in which they come.

Acetone in the presence of ASA acts as a solvent and dissolves the material. In a
controlled manner, the walls of a 3D printed part can be smoothed with minimal dissolution of
the material. This in turn improves aesthetic appearance, water absorptivity resistance, and
strength properties, specifically tensile strength. Rates of water absorptivity are tested using

In order to best control the acetone vapor smoothing process, a vapor smoothing chamber
is created and used. The vapor smoothing chambered, pictured in figures 24 and 25 consists of a
heated bed to accelerate the evaporation of the acetone liquid, a closed chamber, and fans to
circulate a greater amount of vapor onto and around the inserted part. Testing is conducted to
ensure the part is sufficiently smoothed while not sacrificing the structural integrity of the part
(i.e., warping). Figure 26 shows a non-post-processed dog bone sample compared with that of a
post processed dog bone sample. Ideal specimens were placed in chamber for 15 mins with a bed temperature of 72 degrees C.
3 Electrical Connections and Circuits

3.1 Electrical Assembly Schematic

By using repeating geometry and modularity, the solar shingle makes a series electrical connection with adjacent shingles. The circuitry for connecting the solar cells is printed on the shingle using the Voltera Nova printer. Once the traces have been printed, the components (i.e., solar cell and electrical connectors) are fluxed/soldered to the circuit.

The circuit is created inside a dedicated PCB designer, in our case KiCad 7.0. The process involves creating a schematic of the circuit and assigning footprints to the components (figure 27), defining the layout of the circuit (figure 28), routing the traces, creating a 3D model of the circuit, and generating the Gerber files.

The Voltera software processes the Gerber files and allows the user to define various printing parameters. Once parameters have been confirmed, the Voltera printer prints the circuit. Rather than laying copper traces as in traditional PCB manufacturing, the Voltera printer lays a semi-sinterable silver-based ink that is cured. Resistivity differences between copper and the Voltera ink are considered negligible within the scope of this project. The Voltera printer also allows for drilling and reflowing solder for components.
3.1.1 Voltera Nova Anatomy

The Voltera Nova is equipped with both a probing tool as well as an extruder assembly. The probing tool can be set to various “probe pitches”, which determine the frequency of probing; Generally, the more uneven the surface, more surface measurements are required. There are also settings to set the probing tool raise height,
which is critical if the surface you are measuring traverses on areas where the tooling may hit the substrate or installed components.

The extruder is set up similarly; The cooled ink is inserted into the assembly, and heated to 35°C. Depending on the amount of ink required and the surface roughness, extrusion pressure and relief pressure can be fine-tuned to ensure that the ink is continuous and fills the contours of the surface.
3.1.2 Voltera Printing Process and parameters

The base of the shingle is inserted into the Voltera Nova’s workspace, then affixed to the printing area using the included swivel and anchor mounts. The 3D printed substrate was attached at the recesses for the electrical connectors, creating a flat printing area. The electrical connectors protrude into the print area and the bases were marked at these locations. This point was selected for our circuits pivot position; or a reference location for homing the print on the substrate. Flow calibration was then completed using the 250-um nozzle. The printer’s substrate settings were selected as follows:

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Probe Pitch:</td>
<td>2mm</td>
</tr>
<tr>
<td>Probe Raise Height:</td>
<td>5mm</td>
</tr>
<tr>
<td>Extruder Assembly Pressure:</td>
<td>9.3 PSI (400 Units)</td>
</tr>
<tr>
<td>Extruder Relief Pressure:</td>
<td>1.1 PSI (80 Units)</td>
</tr>
<tr>
<td>Trace Width:</td>
<td>0.50mm</td>
</tr>
</tbody>
</table>

*Table 2: Voltera Probe and Extruder Parameters*

When the print has finished, the extruder and probing tool were homed and depressurized. The shingle base with the printed circuit can then be removed from the anchor mounts.

3.1.3 PCB Curing Parameters

Once the trace has been successfully printed, the ink on the substrate is to be cured. The technical data sheet from Voltera recommends the ink is cured at 150°C for 15 minutes. Given that the glass transition temperature of the ASA filament was 106°C, extensive testing was completed to ensure that the traces cured correctly, without changes to the substrate.

Primary testing used a box oven set to 150°C, for a duration of 15 minutes. The result of this configuration led to a sufficiently cured circuit; however, significant warping to the shingle
base was reported, with a nominal deflection of 4mm, and shrinkage of approximately 6% in the X and Y dimension, as well as 6% growth in the Z direction. Secondary testing was conducted in a box oven, set to 135°C, for a duration of 15 minutes. This test also led to a sufficiently cured circuit; however, the base continued to experience severe warping and shrinkage.

Warping during printing is often due to lack of uniformity in temperatures during printing. If the surface layers nearest the heating element heats faster than the rest of the substrate the expansion of the surface will be greater than the interior of the model. With the next testing method, this was the variable that we aimed to adjust. The 3D printed substrate was submerged in a heatsink (Sand), with the only the circuit exposed; This methodology emphasized slowing the sudden heat transfer to the substrate, as it the heatsink would need to be heated more gradually. This method took place in the same box oven at 135°C for 15 minutes. Results for a single shingle base were sufficient, with minimal warping; however, when completed in a batch with 6 shingles, the results were not repeatable and different between all the samples.

Finally, the heated bed on the Voltera One printer was utilized with a ramped heating profile. This method provided direct heat only to the side of the circuit; allowing the rest of the substrate to heat with only conduction. The heating profile is included below:
This method not only cured the circuit sufficiently but provided minimal warping to the shingle base. Shrinkage was negligible, and nominal deflection reached approximately 1.5mm at the bounds of the substrate.

Once the base was cured, the electrical connectors were attached to the circuit using low-temperature solder and epoxy, and the solar cells were pressed into place—with the pads contacting the circuit. The top and bottom assembly were then mated with epoxy, as well as the polycarbonate pane.

3.1.4 Solar Array Circuit

Each line of shingles for a given area of roof exist as a series connection of solar cells within the shingles. Subsequent lines of shingles above or below the aforementioned shingles exist in a parallel connection. Thus, a solar array will consist of both series and parallel connections shown in figure 4. Each series connection of shingles connects to a common bus with respective positive and negative lines.

For series connections of solar shingles, the voltage is multiplied by the number of cells in series. For parallel connections of groups of series connections, the current is multiplied by the
number of groups of series connections. The total power at the common bus is the product of the voltage and the current. For AC applications, the power would need to be converted to AC via an inverter. Though out of scope of this project, in a typical residential solar array, the DC power from the array leads to an inverter which converts the DC power into 240 V AC power, which then connects to the house’s service mains panel.

![Circuit Array Mock Up](image)

*Figure 30: Solar Array Circuit Mock Up on Roof*

4 Data Monitoring and Analysis

In order to efficiently test different solar cell arrangements and electricity losses associated with heat dissipation and resistivity of printed circuits, it is critical to ensure that power generation information is accurate and repeatable. Inconsistent voltage and current measurement could lead to improper sizing of shingle arrays, which could result in improper
sizing of DC inverter, battery, or cost-effective wire gauges. To aid in the design and measurement process, codes and monitors were created in MATLAB and C++.

4.1 Microcontroller Solar Monitoring

Using an Arduino Uno R3 microcontroller, voltage sensor, and a current sensor were connected to create a measurement station. A voltage sensor, current sensor, power, and ground headers were connected in series to the solar cell(s), closing the circuit. On the opposite side of the sensors are pin leads for VCC IN, GRND, and OUT. For the current sensor, the OUT pin was connected to analog pin A2, to monitor the current output from the module in mA. For the voltage sensor, the OUT pin was connected to analog pin A1, to monitor the voltage output from the module in volts. The sensors used a shared ground and did not require a power input in this application. The wiring layout is included below in Figure 31:

![Arduino Solar Monitoring Wiring Diagram](image-url)
Components utilized are included in table 4,

<table>
<thead>
<tr>
<th>Line Number</th>
<th>Description</th>
<th>Photo</th>
<th>Quantity</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5V 60mA Polycrystalline Solar Panel with Epoxy coating 2.67&quot; x 1.45&quot;</td>
<td><img src="image1.png" alt="Photo" /></td>
<td>1</td>
<td>Voltage output range: 0-5 VDC</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Current Output Range: 0-60 mA</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Nominal Efficiency: 23.5%</td>
</tr>
<tr>
<td>2</td>
<td>M/N: 13-340 0-25V Voltage Sensor Module</td>
<td><img src="image2.png" alt="Photo" /></td>
<td>5</td>
<td>Voltage input range: 0-25 VDC Max</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Voltage Detection Range: 0.02445 to 25 VDC</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Voltage Analog Resolution: ±0.00489V</td>
</tr>
<tr>
<td>3</td>
<td>ACS712 0-30A Current Sensor Module</td>
<td><img src="image3.png" alt="Photo" /></td>
<td>1</td>
<td>Current input range: 0-10A Max</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Current Detection Range: 0.0244A to 10 A</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Current Analog Resolution: ±0.0500V</td>
</tr>
</tbody>
</table>
This assembly was used in conjunction with Arduino IDE to print the outputs every 500 Ms via a serial connection. The code is included below:

```c
// Define analog inputs for voltage and current sensors
#define VOLTAGE_SENSOR_PIN A1
#define CURRENT_SENSOR_PIN A2

// Floats for ADC voltage & input voltage
float adc_voltage = 0.0;
float in_voltage = 0.0;

// Floats for resistor values in the voltage divider (in ohms)
float R1 = 30000.0;
float R2 = 7500.0;

// Float for reference voltage
float ref_voltage = 5.0;
```
// ADC Values
int adc_value_voltage = 0;
int adc_value_current = 0;

void setup() {
    // Serial Monitor Frequency
    Serial.begin(9600);
}

void loop() {
    // Read the Analog Inputs
    adc_value_voltage = analogRead(VOLTAGE_SENSOR_PIN);
    adc_value_current = analogRead(CURRENT_SENSOR_PIN);

    // Actual voltage at the voltage sensor input
    adc_voltage = (adc_value_voltage * ref_voltage) / 1024.0;

    // Voltage at the divider input
    in_voltage = adc_voltage * (R1 + R2) / R2;

    int currentSensorInput = adc_value_current;
    int Power_Produced = (currentSensorInput * in_voltage) / 100;

    // Serial Monitor Outputs
    Serial.print("Voltage Sensor (V) = ");
    Serial.println(in_voltage, 2);
    Serial.print("Current Sensor Value (mA) = ");
    Serial.println(currentSensorInput);
    Serial.print("Power Produced (W) = ");
}
Serial.println(Power_Produced,3);
Serial.println("Time Elapsed");
Serial.println(millis());
Serial.println("milliseconds");

// Measurement timer
delay(1000);

Figure 32: Arduino IDE code for outputting current, voltage, and power.

The analog inputs and floats for resistor values were declared at the beginning of the code; the purpose of the floats allow one to define the constant values associated with resistance and the pins to be read from the Arduino. When measuring the voltage output, one must look at the circuit internal to the voltage sensor, seen in Figure 33:

Figure 33, Voltage Sensor Wiring Overview
Within the voltage divider, the Vout can be determined using the expression:

\[ V_{out} = V_{in} \frac{R2}{R1 + R2} \]

The current sensor’s output is measured using a hall effect sensor, internal to the ACS712. The current sensor’s working principle being that when this sensor is placed in the magnetic field generated through the ACS7812s’ conductor, an analog signal, proportional to the current flowing through the sensor (Sanni Shereefdeen et. Al). The outputs are then printed via serial connection to the serial monitoring program, puTTy to tabulate outputs.

4.1.1 Accuracy and correction factor

The accuracy of the voltage sensor can be determined by adding the error from the ADC resolution and voltage sensor error. Arduino Uno boards have a 10 bit ADC, which means that they can represent analog voltages with 1024 values:

\[ 2^{10} \text{ Bits} = 1024 \text{ values of Analog Voltages} \]

Given a reference voltage of 5V (the output voltage of the solar cells selected for the shingle), the resolution error can be estimated using the following equation:

\[ \frac{5V}{1024 \text{ Bits}} = \pm 4.9mV \text{ per shingle} \]

The error associated with the resistors in the voltage divider are rated at 1%. Further, again assuming a reference voltage of 5V, an error of 0.05V can be assumed. This yields a total voltage reading error of \( \pm 0.0549V \).
5.1 MATLAB Selection/Sizing Tools

As the Solar Shingles can be mounted with any number of series of connections, a selection tool uses the dimensional inputs from the solar shingle shell, effective solar area, and roof dimensions to calculate the number of units that will fit, power generated, as well as simulating the roof area with a visual plot. The code is included below in Figure 34:

```matlab
%%To calculate the number of solar shingles to cover a roof and to determine the theoretical power outputs

%% Roof Dims
X = 5;   % width of the roof with shingles (meters)
Y = 10;  % length of the area (in meters)
angle = 30;  % roof angle (in degrees)

%degrees to radians
anglerad = deg2rad(angle);

%%Shingle Stats
numcells_shingle = 1;  % (#)
shingleV_cell = 5;  % Volts
ShingleA_cell = 0.06;  % Amps

%% Shingle Area
shingleW = .1;  % Width of each panel (in meters)
ShingleL = .05;  % Length of each panel (in meters)

% equivalent area from the angle
equX = X / cos(anglerad);
```
% Width, number of rows
num_rows = floor(equX / shingleW);

% length, number of panels
num_columns = floor(Y / ShingleL);

% number of panels needed
total_panels = num_rows * num_columns;

% Shingle Array Stats
ShingleV_total = numcells_shingle * shingleV_cell;
ShingleA_total = num_rows * ShingleA_cell;
Powerout = ShingleA_total * ShingleV_total;

% Results
fprintf('Roof Dimensions (X x Y): %.2f m x %.2f m
', X, Y);
fprintf('Roof Angle: %.2f degrees
', angle);
fprintf('Shingle Dimensions (Width x Length): %.2f m x %.2f m
', shingleW, ShingleL);
fprintf('Equivalent width: %.2f m
', equX);
fprintf('Number of Rows: %d
', num_rows);
fprintf('Number of Columns: %d
', num_columns);
fprintf('Total number of shingles needed: %d
', total_panels);
fprintf('Total Theoretical Power Output: %d Watts
', Powerout);

% Plot on graph
for i = 1:num_rows
    for j = 1:num_columns
        x = (i - 1) * shingleW;
        y = (j - 1) * ShingleL;
        rectangle('Position', [x, y, shingleW, ShingleL], 'EdgeColor', 'b');
    end
end
axis([0, X+3, 0, Y+3]);
xlabel('Width (m)');
ylabel('Length (m)');
title('Simulated roof');

Figure 34, Matlab Selection Tool
A sample output for this code with the given parameters (X, Y, angle, numcells_shingle, ShingleV_cell, ShingleA_cell, ShingleW, ShingleL) the following plot, shown in figure 35, can be created:

![Simulated roof](image)

**Figure 35, MATLAB Selection Tool Output**

Using this selection tool in conjunction with the Arduino program, one can compute the peak power output using voltage and current values from the power monitor.

### 5.2 Trends Associated with Measurement

On a clear, sunny day, a solar shingle was attached to the Arduino power monitor to collect power generation data over three hours. The serial monitoring program putTty was used to save the outputs to a text file, which was delimited to allow for plotting of the data. The plots seen in Figure 36 shows that the voltage is exceptionally steady, indicating a steady resistance in the circuit. Small drops in voltage, current, and power graphs are from cloudy weather.
Figure 36: Arduino Power Monitor Output, One shingle
6 Testing Methodology

6.1 Power Generation Efficiency

![Figure 37: Solar Cell vs Solar Shingle Performance](image)

6.1.1 Circuit Performance

To evaluate the performance of the circuits created by the Voltera Nova on ASA substrates, a multimeter was used to measure the resistance across traces with known
dimensions, the resistivity of the silver-based conductive ink can be determined. The approach taken is seen below:

**Resistance of a Wire:**

\[
R = \frac{\rho L}{A}
\]

As we know the dimensions of the traces (L, W, T); we can determine the resistivity of the conductive material:

\[
\rho = \frac{RA}{L}
\]

<table>
<thead>
<tr>
<th>Geometric Properties of the Trace</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Length (L)</td>
<td>71.9 mm (0.0719 m)</td>
</tr>
<tr>
<td>Width</td>
<td>0.5 mm (0.0005 m)</td>
</tr>
<tr>
<td>Thickness</td>
<td>0.07 mm (0.00007 m)</td>
</tr>
<tr>
<td>Cross Sectional Area (W*T)</td>
<td>0.035 mm (3.5x10^-8 m)</td>
</tr>
<tr>
<td>Measured Resistance</td>
<td>1.9 Ω</td>
</tr>
</tbody>
</table>

*Table 5: Trace Properties for Resistivity Calculation*

\[
\rho = \frac{(1.9 \, \Omega)((3.5 \times 10^{-8} \, m^2))}{0.0719 \, m}
\]

Therefore, the resistivity of the cured, silver-based ink can be calculated as:
\[ \rho = 9.248 \times 10^{-7} \Omega \cdot m \]

Using this material property, one can estimate the resistance of a Voltera-printed circuit, given the geometry.

### 6.2 Water Absorptivity

Water absorptivity testing is used to determine the rate of water absorption in a specimen after being submerged and dried. The content of water remaining in the material is closely related to the mechanical strength and electrical insulation resistance of the specimen. Water Absorptivity testing was completed using a 3D printed ASA specimen, governed by the standard included in ASTM D570. This test, for molded plastics, is composed of a disk with 2.0” diameter and 0.125” thickness. The specimen is weighed immediately after being printed. The specimen is then submerged in a container of distilled water at 73° F for 24 hours. The sample is then weighed again following the submersion.

<table>
<thead>
<tr>
<th>Dry Sample</th>
<th>Wet Sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight: 0.016 lb</td>
<td>Weight: .018 LB</td>
</tr>
<tr>
<td>Dimensions:</td>
<td>Dimensions:</td>
</tr>
<tr>
<td>Diameter: 1.993”</td>
<td>Diameter: 2.009”</td>
</tr>
<tr>
<td>Thickness: 0.1251”</td>
<td>Thickness: 0.1257”</td>
</tr>
</tbody>
</table>

*Figure 38: Wet vs Dry Sample Properties*

\[
\text{Increase in weight,} \% = \frac{\text{Wet Weight} - \text{Conditioned Weight}}{\text{Conditioned Weight}} \times 100
\]

\[
\text{Increase in weight,} \% = \frac{0.018 \text{ lb} - 0.016 \text{ lb}}{0.016 \text{ lb}} \times 100
\]

\[
\text{Increase in weight,} \% = 3.3 \%
\]
7  **Test Results**

From section 6.1, The circuits and electrical connectors create a power loss of approximately 7.4% in comparison to the power generated independently by the solar cell. A single shingle produces on average 0.25 watts on a sunny day. In Section 6.2, the resistivity of the cured traces was calculated to be $9.248 \times 10^{-7} \Omega \cdot m$, which is less desirable than traditional cold-drawn copper; however, this could be improved by increasing the cross-sectional area of the traces (Width and Thickness). In section 6.3, water absorptivity was determined to be approximately 3.3%, which could also be further improved with further acetone vapor smoothing.

8  **Costs/ Bill of Materials**

The BOM currently only contains the quantity of parts going towards a prototype solar shingle rather than an entire diorama roof.

<table>
<thead>
<tr>
<th>Line Number</th>
<th>Description</th>
<th>Photo</th>
<th>Quantity</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5V 60mA Polycrystalline Solar Panel with Epoxy coating</td>
<td>![Image]</td>
<td>10</td>
<td>$16.00 Total</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$1.60 EA</td>
</tr>
<tr>
<td>2</td>
<td>Magnetic POGO Pin Connector</td>
<td>![Image]</td>
<td>1</td>
<td>$4.00 EA</td>
</tr>
<tr>
<td>3</td>
<td>ASA Filament (Bambu Labs)</td>
<td>![Image]</td>
<td>1 Spool</td>
<td>$29.99 per kg</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>31.93 grams required (At 100% infill)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Total cost: $0.96</td>
</tr>
<tr>
<td>Line</td>
<td>Description</td>
<td>Photo</td>
<td>Quantity</td>
<td>Cost</td>
</tr>
<tr>
<td>------</td>
<td>-------------</td>
<td>-------</td>
<td>----------</td>
<td>------------</td>
</tr>
</tbody>
</table>
| 4    | Voltera Conductive Ink | ![Image](image1.png) | 1 | $99.99 per 2 mL  
~0.10 mL used per shingle.  
Total Cost:  
$5.00 per shingle |
| 5    | 12”x14” Polycarbonate Sheet | ![Image](image2.png) | N/A | $9.98 EA  
Total Cost:  
$0.50 per shingle |
| 6    | Epoxy Sealant | ![Image](image3.png) | 1 | $8.00 EA  
~5% used per shingle.  
Total Cost:  
$0.40 per shingle |

**Total cost per shingle:** $12.10

Table 6: Solar Cell Bill of Materials

Power Monitor Part List:

<table>
<thead>
<tr>
<th>Line Number</th>
<th>Description</th>
<th>Photo</th>
<th>Quantity</th>
<th>Cost</th>
</tr>
</thead>
</table>
| 1           | M/N: 13-340  
0-25V Voltage Sensor Module | ![Image](image4.png) | 1 | $1.25 EA |
| 2           | ACS712 0-30A Current Sensor Module | ![Image](image5.png) | 1 | $4.00 EA |
9 Conclusion

This project required a lot of iterative design, and manufacturing. Many of the obstacles faced were attributed to 3D printing and circuitry printing causing warping on the shingle body. After many attempts however, a successful, reproducible process was developed to 3D print the shingle body, print the internal circuit on the 3D printed substrate, and cure the conductive ink without warping the part.

With the final design of the solar shingle, the manufacturing could also be automated. Without internal wiring, manual labor for soldering is not required, as all soldering is done at defined points, without the need to orient components. This way, an automated line could be created to turn raw materials into the finished shingles.
9.1 **Accomplishments**

While we did not achieve everything, we set out to accomplish, there are many milestones we were able reach. Our result of this project was a prototype that successfully:

- Shed water utilizing the sleek design and overlapping joints
- Fit tightly together after many design iterations and tolerance changes
- Used the Voltera printer’s conductive ink on an ASA 3D printed surface to make a circuit
- Electrically connected electrical components to a conductive ink trace through soldering
- Combined commercially available and 3D printed components to streamline our design process
- Met the roofing fire codes by using ASA filament and polycarbonate materials
- Interfaced and locked together with adjacent prototypes to create a robust connection
- Generated power as a single shingle and as an array of shingles
- Cost significantly less than other solar shingle alternatives on the market
- Connected with our microcontroller solar monitoring device
- Granted our team a Design Day award

The academic impact of this design project is significant and covers multiple elements of mechanical engineering. We put into practice a variety of methods and tools for concept generation, solution evaluation, risk assessment and iterative design changes. The team planning and discussion will continue to enhance our readiness for the workforce and/or postgraduate studies. In addition, the structured decision matrices that we generated will allow us to understand how to make more well-informed decisions on this and future projects and how to execute them.
9.2 Sources of Error

As with any project there were several sources of error that provided difficulty in the design and assembly of the finished product. The two most considerable points were working with unexpectedly small tolerances based on prototyping constraints and temperature material limitations.

Initially, when considering how best to prototype the solar shingle, subsystem parts were selected, such as the electrical connectors and the solar cell, which were cost effective and ubiquitous with respect to procurement. This led to a relatively single shingle prototype which led to difficulty in controlling the tight tolerances during assembly. Between the FDM printer for the solar shingle structure and the Voltera NOVA circuit printer, there was very little room for error. A single prototype was non-performant if the electrical connector, or circuit were off by as little as a millimeter.

ASA was ultimately chosen as the shingle material due to its excellent UV resistance. During initial research, it also met the temperature requirements for what a shingle may experience on a rooftop (i.e., approximately 70 C). Upon bringing the use of the Voltera NOVA printer within scope of the project, a curing process for the electrical traces around 150 C was required. As the glass transition temperature of ASA is approximately 100 C, this caused shrinking and warping of the shingle bases. Ultimately, a ramped temperature profile for the cure allowed for a limited shrinking and warping.
9.3 Ethical and Environmental Considerations

By using additive manufacturing techniques, material consumed is much lower than what would have been consumed; had milling or similar techniques been used. This is because when using FDM techniques, only the material that is required is extruded.

It is an engineer’s responsibility to promote the growth of products and designs that sustain the safety and well-being of the community, especially as a sustainable and reliable energy source is required as the societal needs for electricity continue to increase each year. By creating a solar shingle that is less cost prohibitive, both the consumer and environment benefit; the demand of local power grids could be lessened aiding in a reliable electrical infrastructure and decreased risk of power transmission blackouts (brown outs) (Adithya Ramanujam Indian Institute of Technology, et al.).

10 Future Work to be Completed

10.1 Material Strength Testing

Future work includes the process to conduct tensile tests with dog bone specimens made of ASA material in two different print orientations to determine the stress required for layer separation and for maximum strength when the dog bone is printed flat against the print bed. Tensile tests completed would follow ASTM code D638-14, or the “Standard Test Method for Tensile Properties of Plastics.” Mechanical properties of 3D printed ASA are also available from
jlcpcb.com, a plastic filament supplier. They show results for the Young’s Modulus, tensile strength, and elongation at break according to ASTM D638 as shown in Figure 38.

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Test Method</th>
<th>Value</th>
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<tbody>
<tr>
<td>Young’s modulus (X-Y)</td>
<td>ASTM D638 (ISO 527, GB/T 1940)</td>
<td>2379 ± 157 (MPa)</td>
</tr>
<tr>
<td>Tensile strength (X-Y)</td>
<td>ASTM D638 (ISO 527, GB/T 1940)</td>
<td>43.8 ± 0.8 (%)</td>
</tr>
<tr>
<td>Elongation at break (X-Y)</td>
<td>ASTM D638 (ISO 527, GB/T 1940)</td>
<td>8.7 ± 0.8 (%)</td>
</tr>
</tbody>
</table>

Figure 38, ASA Material Properties

10.1.1 Environmental Testing

We plan to conduct the same tensile tests of the filament after the dog bone specimens have been exposed to various environmental conditions. We plan to expose these different specimens to elevated temperatures, high humidity, UV radiation chambers and possibly other conditions yet to be considered.
11 References


[4] Nave, Dr. R. “Resistance.” Resistance and Resistivity, Georgia State University, 1 Aug. 2000, hyperphysics.phy-astr.gsu.edu/hbase/electric/resis.html.
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<td>18</td>
<td>Type C SolidWorks Assembly Array</td>
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<td>20</td>
<td>3D Printed Type D Assembly</td>
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<td>21</td>
<td>Final Type D Assembly: Exploded View</td>
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<td>22</td>
<td>Final Type D SolidWorks Assembly</td>
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<td>3</td>
<td>Curing Ramp Curve Parameters</td>
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<td>Trace Properties for Resistivity Calculation</td>
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<td>7</td>
<td>Solar Monitor Bill of Materials</td>
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</table>

14 Codes and standards used

<table>
<thead>
<tr>
<th>Code/Standard Utilized</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>Chapter 9 Roof Assemblies of the 2019 Residential Code of Ohio</td>
<td>Govern the design, materials, construction, and fire prevention measure required for a residential roof in Ohio.</td>
</tr>
<tr>
<td>--------------</td>
<td>---------------------------------------------------</td>
</tr>
</tbody>
</table>
