1.0 Name:

2.0 Project Title: Computational Aid for Designing PV Canopy for Solar-Powered Transit

3.0 Background:

It is necessary to understand the current state of the global transportation sector before introducing a solution: automated transit networks (ATNs). ATNs have potential to be powered by solar energy through use of photovoltaic (PV) canopies. PV systems can be designed and modeled with software to determine their outputs and configurations, but no software currently exists to design PV systems for ATNs. These four topics are subsequently discussed.

Current State of Transportation

The current state of the global transportation sector is energy intensive, dangerous, and inefficient. It is energy intensive in that it comprises 25% of the total world energy consumption [1]. This statistic rises to 28% for the United States, with the primary energy source being petroleum [2, p. 305]. The combustion of petroleum creates greenhouse gases like carbon dioxide and methane, which trap heat in the atmosphere and contribute to global warming [3]. Transportation emissions represented 28% of the United States greenhouse gas production in 2016, with 60% of these emissions coming from light-duty passenger vehicles [4]. Besides the environmental impact, transportation emissions also have adverse health effects. An example is in the rapid rise of passenger cars in China, illustrated by the doubling of cars in Beijing to 5 million over a five-year span [2, p. 356]. China was subsequently determined to contain 16 of the 20 most air-polluted cities in the world, with one-third of the country's urban residents exposed to unsafe air pollution levels [2, p. 356]. Aside from pollution, car-based transportation is susceptible to lethal accidents caused by small distractions. Road traffic crashes caused 1.25 million global fatalities in 2013, becoming the primary cause of death among the 15-29 year age-group [5]. Finally, urban congestion makes car-based transportation inefficient, as the average U.S. driver spends 443 hours driving per year, 100 of which are in bumper-to-bumper traffic [2, p. 359].

Automated Transit Networks (ATNs)

A developing solution to the modern transportation problem is the ATN. An ATN is a fully connected network of guideways and stations, within which small autonomous vehicles carry passengers directly to their destinations without transfers or stops [6, p. 7]. The concept has been in existence since the 1950s and five ATNs are currently in operation around the world [6, p. 1]. ATNs are more efficient than car-based transportation because they travel directly from origin to destination with no possibility of congestion. They are safer than cars because they operate on isolated guideways, eliminating the possibility of collision with pedestrians, cyclists, and vehicles. Finally, ATNs are less energy intensive because they are electrically powered with higher efficiencies than internal combustion engines. With the exponentially decreasing cost of solar PV modules, it is now practical to power ATNs with solar energy [7]. This would make these networks self-sufficient with zero emissions, yielding potential to drastically reduce greenhouse gas production.

There is an international effort to design solar-powered ATNs, with local effort exhibited by the Spartan Superway program at San José State University. The objective of this program is to develop partial and full-scale solar-powered ATNs for public exhibitions and, ultimately, implementation in Silicon Valley [8, p. 1]. A necessary step is to model the associated PV systems to understand the electricity production, losses, and costs. This information would also provide a basis for developments related to electrical systems, energy storage, vehicle throughput, and cost analysis.

Modeling PV Systems

A PV cell is a specially doped semiconductor that produces a flow of electrons from the excitation of incident photons [9, pp. 50-51]. Single PV cells generally produce less than 5 W at 0.5 V_{DC} and therefore need to be wired in series-parallel configured modules for high-power applications [9, p. 49]. Modules can be wired into arrays for even larger applications.

Solar irradiance is the power density of sunlight and is dependent on the weather and angle of incidence [9, p. 28]. Since the position of the sun relative to a location on Earth can be calculated, it is useful to develop a computer program to simulate the changing angle of incidence of the sunlight onto the PV module. Weather effects can be incorporated by utilizing a database of weather station records. One such archive is the National Solar Radiation Database, which uses a combination of weather station data and meteorological models to predict the weather effects on solar irradiance [10]. Once the solar irradiance on the PV module is determined, losses from the module efficiency, inverter efficiency, and other factors are incorporated. Many commercial and free programs exist for designing PV systems for industrial buildings, homes, and solar farms. Three popular programs are the System Advisory Model (SAM) by the National Renewable Energy Laboratory (NREL) [11], HelioScope by Folsom Labs [12], and SunDAT by FTC Solar [13]. These programs are limited to the design of planar PV arrays, in which all modules are arranged on either a single plane (as on a sloped residential rooftop) or parallel planes (as on a flat industrial rooftop). After a thorough literature review, no PV design software was discovered that could model arrays in non-planer configurations, as would be required for the design of PV canopies for transit applications.

PV Canopies for Transit Applications

PV canopies are elevated arrays of PV modules that provide shade, shelter, and electricity generation [14]. They are commonly built above parking lots, around the perimeter of buildings, and over transit stations. The primary benefits of PV canopies are that they do no compete with other land use and are located where the generated electricity is used, avoiding transmission losses [2, p. 320]. Since these canopies are usually in public places, it is important for them to be aesthetically pleasing [9, p. 220]. They must also be structurally sound throughout various loading modes like module weight, strong winds, and possible accumulation of snow [9, p. 221].

Finally, the orientation of the arrays must be optimized to maximize the system electricity production and economic payback.

The application of PV canopies for solar-powered transit is unique in that the canopy extends over the top of the track. This protects the track and vehicles from exposure to sunlight and weather, with opportunities for rainwater management through gutters or storage tanks. The canopy bearing is defined by the direction of the track, creating situations for non-ideal west or east-facing panels. Additionally, the aesthetics of the canopy are of great importance because these transit systems are intended to service popular city locations and become part of the city image. Curved PV canopies have become common in architectural renderings and the efficiency of these configurations will be under investigation [8, p. 2]. The tilt of the array over each leg of track will need to be optimized, and an investigation will be conducted on the effects of using different array profiles for north-south track versus east-west track. Existing PV system design software cannot perform these optimizations for transit routes, establishing the need to develop a new program. This development is the primary subject of the project and will include the associated investigations and validations outlined in the Methodology section.

4.0: Objectives:

The objectives of the project are to:

- document the development of a MATLAB program that inputs route information and component properties, and outputs the optimal PV canopy configuration and simulated annual electricity generation.
- investigate the efficiencies of curved versus planar PV arrays.
- investigate the use of different PV canopy profiles for legs of track with different bearings.
- investigate the use of thin-filmed versus crystalline PV modules.
- provide a basis for future ATN developments about electrical system design, energy storage, vehicle throughput, and cost analysis.

5.0 Methodology:

1. Research:
    a. ATN technology and solar-powered transit
    b. MATLAB coding techniques
    c. Solar incidence modeling methods
    d. Weather modeling
    e. Solar irradiance data acquisition techniques
    f. PV module technology
    g. Optimization algorithms
    h. PV system components and losses
2. Develop the solar simulation code to calculate the solar irradiance incident on the transit route. This will be comprised of:
    a. Route Input Code: Extract the footprint and bearing of the PV canopy from a user-defined graphical route.
    b. Solar Modeling Code: Simulate the hourly position of the sun relative to the central coordinates of the route. Then acquire hourly weather data for the entire year at this location. Combine these to determine the amount of irradiance received.
3. Validate the solar simulation code:
    a. Compare with the simulated hourly irradiance results on a leg of track from:
        i. NREL SAM
        ii. Folsom Labs HelioScope
        iii. FTC Solar SunDAT
    b. Compare with experimental data:
        i. Design and build an Arduino-based PV module test fixture to measure the solar irradiance throughout one day.
        ii. Compare the simulated results to the experimental results.
    c. Refine code as necessary.
4. Conduct studies with the validated solar simulation code to gain information for the optimization code:
    a. Simulate the efficiency of curved versus planar PV arrays. Determine the amount of curvature that should be applied to balance efficiency with aesthetics.
    b. Simulate the efficiency of planar/curved versus hemispherical PV arrays for different track bearings. Determine the value of using different PV array profiles for different track bearings.
    c. Simulate the use of flexible thin-film versus rigid crystalline PV modules. Determine which type of module should be used.
5. Develop the optimization code to optimize the tilt or profile of the PV canopy for each leg of track.
6. Develop the electricity generation code to incorporate system losses for the simulation of electricity generation for every hour of the year.

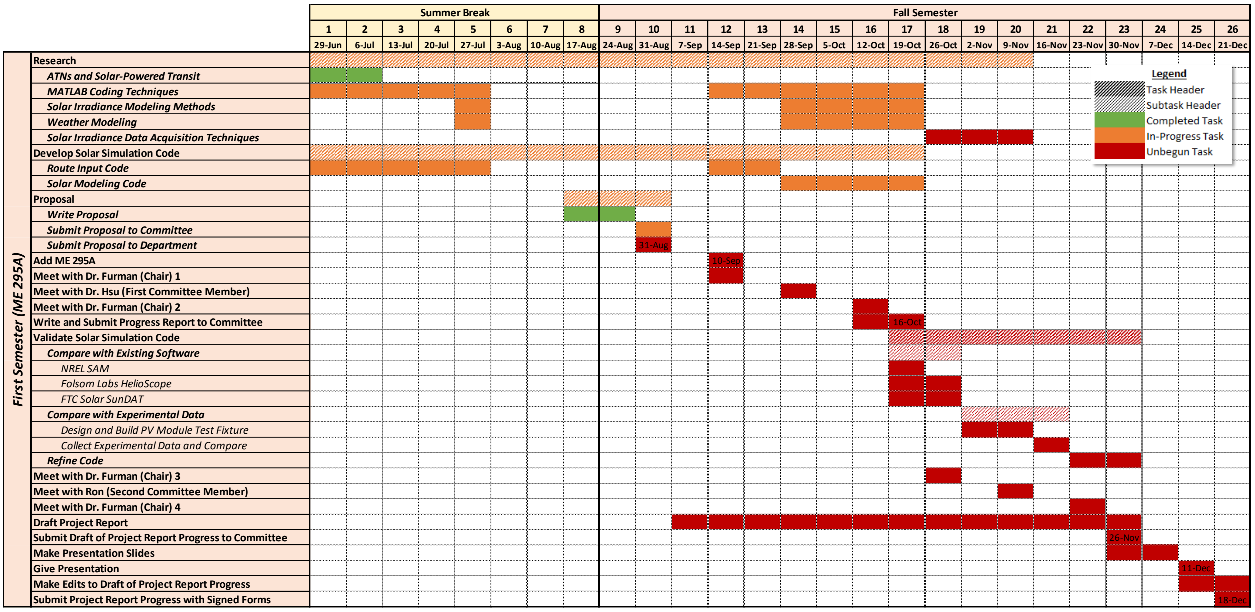
7. Develop the results code to output meaningful results from the simulation. These include:
    a. Total number of PV modules
    b. Total annual electricity generation
    c. Day of maximum electricity generation
    d. Day of minimum electricity generation
    e. Estimated cost of PV system
    f. Map of route with legs and stations labeled
    g. CSV file with the optimal tilt and profile of the PV canopy for each leg
    h. CSV file of the generated electricity for every hour of the year
8. Validate the completed code:
    a. Compare with the simulated hourly electricity generation results on a leg of track from:
        i. NREL SAM
        ii. Folsom Labs HelioScope
        iii. FTC Solar SunDAT
    b. Compare with experimental data from the Arduino test fixture.
    c. Refine code as necessary.

6.0 Deliverables:

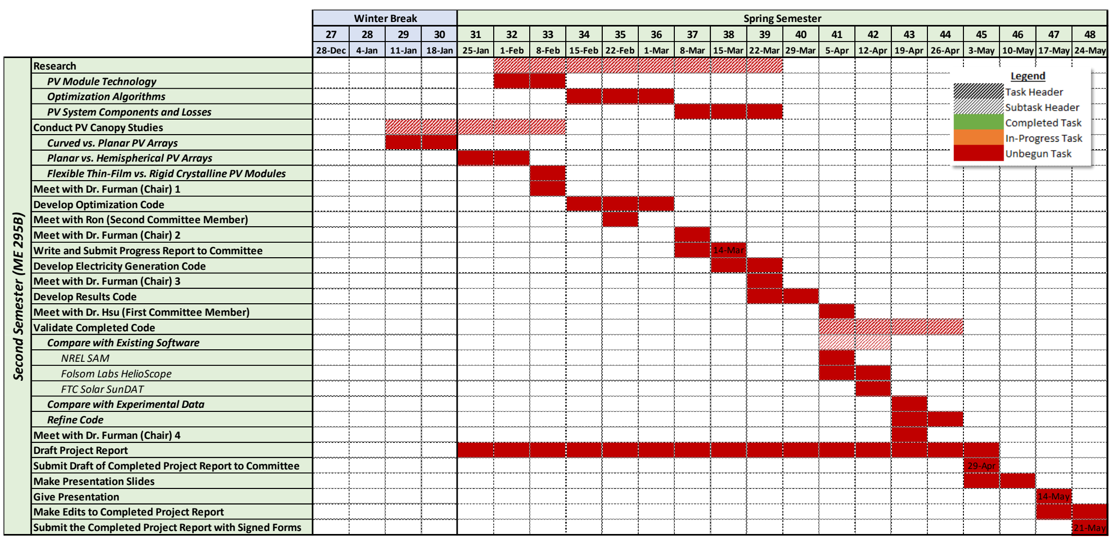
The deliverables for the project are:

- the MATLAB code for designing and simulating a PV canopy for solar-powered transit networks.
- documentation of the development of the code, including results from investigations on PV array orientation, profile, and module type, in the form of the finished project report.

7.0 Timeline:



Summer Break
Fall Semester
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26
29-Jun 6-Jul 13-Jul 20-Jul 27-Jul 3-Aug 10-Aug 17-Aug 24-Aug 31-Aug 7-Sep 14-Sep 21-Sep 28-Sep 5-Oct 12-Oct 19-Oct 26-Oct 2-Nov 9-Nov 16-Nov 23-Nov 30-Nov 7-Dec 14-Dec 21-Dec
First Semester (ME 295A)
Research
ATNs and Solar-Powered Transit
MATLAB Coding Techniques
Solar Irradiance Modeling Methods
Weather Modeling
Solar Irradiance Data Acquisition Techniques
Develop Solar Simulation Code
Route Input Code
Solar Modeling Code
Proposal
Write Proposal
Submit Proposal to Committee
Submit Proposal to Department
Add ME 295A
Meet with Dr. Furman (Chair) 1
Meet with Dr. Hsu (First Committee Member)
Meet with Dr. Furman (Chair) 2
Write and Submit Progress Report to Committee
Validate Solar Simulation Code
Compare with Existing Software
NREL SAM
Folsom Labs HelioScope
FTC Solar SunDAT
Compare with Experimental Data
Design and Build PV Module Test Fixture
Collect Experimental Data and Compare
Refine Code
Meet with Dr. Furman (Chair) 3
Meet with Ron (Second Committee Member)
Meet with Dr. Furman (Chair) 4
Draft Project Report
Submit Draft of Project Report Progress to Committee
Make Presentation Slides
Give Presentation
Make Edits to Draft of Project Report Progress
Submit Project Report Progress with Signed Forms
31-Aug
10-Sep
16-Oct
26-Nov
11-Dec
18-Dec
Legend
Task Header
Subtask Header
Completed Task
In-Progress Task
Unbegun Task



Winter Break
Spring Semester
27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48
28-Dec 4-Jan 11-Jan 18-Jan 25-Jan 1-Feb 8-Feb 15-Feb 22-Feb 1-Mar 8-Mar 15-Mar 22-Mar 29-Mar 5-Apr 12-Apr 19-Apr 26-Apr 3-May 10-May 17-May 24-May
Second Semester (ME 295B)
Research
PV Module Technology
Optimization Algorithms
PV System Components and Losses
Conduct PV Canopy Studies
Curved vs. Planar PV Arrays
Planar vs. Hemispherical PV Arrays
Flexible Thin-Film vs. Rigid Crystalline PV Modules
Meet with Dr. Furman (Chair) 1
Develop Optimization Code
Meet with Ron (Second Committee Member)
Meet with Dr. Furman (Chair) 2
Write and Submit Progress Report to Committee
Develop Electricity Generation Code
Meet with Dr. Furman (Chair) 3
Develop Results Code
Meet with Dr. Hsu (First Committee Member)
Validate Completed Code
Compare with Existing Software
NREL SAM
Folsom Labs HelioScope
FTC Solar SunDAT
Compare with Experimental Data
Refine Code
Meet with Dr. Furman (Chair) 4
Draft Project Report
Submit Draft of Completed Project Report to Committee
Make Presentation Slides
Give Presentation
Make Edits to Completed Project Report
Submit the Completed Project Report with Signed Forms
14-Mar
29-Apr
14-May
21-May
Legend
Task Header
Subtask Header
Completed Task
In-Progress Task
Unbegun Task

8.0 References:

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