2013 IMSA Annual Conference

Solar Powered Warning Light System Design

July 20, 2013

Presented by Ted Vaeches of Traffic Safety Corp.
Solar Powered Warning Light System Design

➢ Our Focus Today
  ▪ Integrated Solar Powered Systems Used for Warning Light Systems
  ▪ Characteristics
    ▪ Integrated - Solar Panel, Storage Battery, Charge Controller, and System Controller
    ▪ Independent System - Not tied to an AC Utility Grid
    ▪ Low Power - Connected to LED Devices, Intermittent DC Loads

In-Roadway Warning Lights
LED Edge Lite Signs
LED Beacons
Solar Powered Warning Light System Design

Session Objectives – Survey Class on Solar Power System Design
- Survey of Enabling Technologies

Design Example
- Develop an Appreciation of System Requirements
- Define a Set of Performance Criteria
- Examine the Effects of Environmental Factors and Component Limitations on System Performance

System Installation Effects on System Performance

Solar Powered System Benefits

Solar Power System Deployment Limitations
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- Presentation Ground Rules
  - Ask Questions and Offer Options
  - Be Sensitive to Our Time Restrictions
    - Keep Questions and Responses Concise and Focused
    - More Detailed Discussions – At the End of Presentation, TSC Booth, or Call or Email
  - Copy of Presentation Available
    - Provide Business Card, or Send me an Email Request with Your Phone Number
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- **Audience Poll**
  - Experience Designing a Solar Powered Systems?
  - Experience Specifying a Solar Powered Systems?
  - Experience Installing or Maintaining a Solar Powered System?
  - Involved in a Current, or Near Term, Solar Powered System Project?

Let’s Begin
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- **Enabling Technologies – Two Groups (Energy Converting and Energy Controlling)**
  - **Energy Converting**
    - **Solar Panels** - Devices that Convert Wide Spectrum Solar Energy into Electrical Energy
      - Cost Decreasing, Efficiency Increasing, and Quality Improving
    - **Batteries** - Devices that Convert Electrical Energy into Chemical Energy for Storage, and then Back Again into Electrical Energy
      - Higher Energy Density, Service Life Increasing, Safer
    - **Light Emitting Diodes** - Devices that Convert Electrical Energy into Narrow Spectrum Light Energy
      - Cost Decreasing, Lumens/Watt Increasing, Useful Life Expectancy Increasing
  - **Energy Controlling**
    - **Charge Controllers** - Control the Flow of Electrical Energy Between System Components
      - More Sophisticated in Protecting Batteries and Maximizing Energy Transfer
    - **System Controllers** - Control the Flow of Energy to all External Loads and Interfaces with the System’s Activation Devices
      - More Sophisticated in Digitally Controlling Flash Durations and Patterns, and more Flexible in Interfacing with Activation Devices
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- **Solar Panels**
  PV Cell → PV Module/Panel (Encapsulated Assembly) → PV Modules/Panel → PV Array (Group of Panels)

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**PV Cell**
- Antireflective Coating
- Front Contact
- Negative Layer
- Positive Layer
- Back Contact
- Sunlight

**Encapsulated Assembly**
- Aluminium Frame
- Tough Glass
- Non-Reflective Layer
- Electrical Connections
- n-type Silicon Wafer
- p-type Silicon Wafer
- Backing Layer

**PV Cells**
- Connected in a Solar Module

**Panels Making Up An Array**
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- Sun's Energy Spectrum at Top of Atmosphere and at the Surface of the Earth

Key Relationships
- Wavelength & Frequency (Inverse)
- Frequency & Energy Content (Direct)
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- **Solar Cell Device Physics**
  - For Current to Flow in a Solar Cell *Energy from Sun Light must be Absorbed* by the Valance Electrons which are Bound to the Atoms
  - The **Minimum Energy** Required for Absorption to take Place is Called the **Band Gap Energy**
  - When Energy is Absorbed by the Valance Electrons they Jump to the **Conduction Band** and Current Flows
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- Minimum Energy Required for a Photon to be Absorbed by a Valance Electron

**Note:** Energy Expressed in Electron Volts
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- Energy of the Electromagnetic Spectrum Expressed in Electron Volts
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- **Batteries**
  - Batteries have been around for a long time

  **Baghdad Battery/Parthian Battery**
  250 BC – 224 AD
  First Battery?

  **Modern Day VRLA Battery**
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- **Batteries**
  - A Battery is a Chemical Device and depends on Chemical Reactions to Store and Release Energy.

![Diagram of Battery Discharging and Charging]
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- Batteries
  - Lead Acid Batteries
    - In a lead acid battery, the electrodes are made from lead. The electrolyte is sulfuric acid. Hence the name “Lead-Acid”. Rechargeable Battery!
  - VRLA battery (valve-regulated lead–acid battery)
    - More commonly known as a sealed battery is a lead acid rechargeable battery.
    - Because of their construction, VRLA batteries do not require regular addition of water to the cells, and vent less gas than flooded lead-acid batteries.
  - VRLA Classifications
    - Absorbed Glass Mat (AGM) Battery: An absorbed glass mat battery has the electrolyte absorbed in a fiber-glass mat separator.
    - Gel battery: A gel battery (also known as a "gel cell") is a VRLA battery with a gelified electrolyte; the sulfuric acid is mixed with silica fume (fine particles of sand), which makes the resulting mass gel-like and immobile.
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- **Batteries**
  - Batteries are not Perfect Voltage Sources, they have Internal Resistance

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**Physical Battery**

- Ideal Battery
- Internal Battery Resistance

**Internal Resistance**
- Ambient Temperature
- Discharge Rate
- Chemical Properties
- Battery Age
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- **Charge Controllers**
  - Major Function – Prevent Over Charging and Undercharging of the Battery
  - Other Functions
    - Prevents Against Excessive Discharging of Battery (Load is Disconnected)
    - Prevents Discharging of Battery through Solar Panel at Night
    - Temperature Sensor to Adjust Battery Voltage Levels to Optimal Levels
    - Status and Error Indicators – Battery State of Charge, Load Fault Conditions
  - Two Main Types – Pulse Width Modulated (PWM) and Maximum Power Point Tracking (MPPT)
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- **Pulse Width Modulated Charge Controller**
  - A **Pulse Width Modulation (PWM)** type of Charge Controller Varies the Width of the Charging Pulses to Maintain the Appropriate Charging voltage on the Batteries Depending on the Charging Phase (Bulk, Absorption, or Float)
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- **Maximum Power Point Tracking Charge Controller**
  - A MPPT, or Maximum Power Point Tracker is an Electronic DC to DC converter that optimizes the match between the Solar Panel, and the Storage Battery.
  - Most 12 volt Solar panels are designed to put out around 17 Volts
  - While Charging, Most Batteries Operate in the Range of 12.6 to 14.4 Volts
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- **Light Emitting Diodes (LEDS)**
  - **Light-emitting diode (LED)** is a Solid State (Diode) light source.
  - **Light Emission**: When a light-emitting diode is switched on, electrons release energy in the form of photons. This effect is called electroluminescence and the color of the light (corresponding to the energy of the photon) is determined by the energy band gap of the semiconductor.

Example: CREE XP-E
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- Light Emitting Diodes (LEDS)
  - High Luminous Efficacy (Lumens/Watt)
  - Narrow Spectrum
  - Long Useful Life Expectancy

![Graph showing relative radiant power by wavelength for different colors](image)

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- Light Emitting Diodes (LEDS)
  - Small Increases in Forward Voltage Create Large Changes in Forward Current
  - Increasing Forward Current Increases the Light Output of the LED
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- Light Emitting Diodes (LEDS)
  - To Maintain the Long Life Expectancy of an LED Proper Thermal Heat Sinking is Required
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➢ System Controller

System Controller Functions
- Generates MUTCD Standard Flash Patterns
- Generates Enhanced Flash Patterns
- Auto-sequencing of Flash Pattern Mode
- Flexible Interfacing to Activation Devices
- Digital Control the Activation Duration
- Dual Outputs with Selectable Flash Patterns
- Continuous Flashing Pattern Mode
- Battery Charge Controller and Battery
- Multiple Disconnects - Solar Panel, Storage Battery, and Load
- Lightning Surge Protection

TS1100 System Controller
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- Design Example: In-Roadway Warning Light System
  - System Description
    - Site Location: **WACO, TX, ZIP Code 76701**
    - **Site Description**: Four Lanes of Traffic, Two in Each Direction, Plus a Turn Lane
      Simple Push Button Activation at Each side of the Crosswalk
      Enhanced LED Edge Lit Signs at Each Side of the Crosswalk
    - **MUTCD Requirement for the use of In-Roadway Light Fixtures**: 2 Fixtures / Lane for a total of 10
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- Design Example: In-Roadway Warning Light System
  - Equipment Specification
    - Light Fixture → (10) TS600 (Bi-Directional, Flush Profile Fixtures)
    - Enhanced LED Edge Lit Sign → (2) TS30
    - System Activation → (2) AC-X2 Push Button
    - System Controller → (1) TS1100SP
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- Design Example: In-Roadway Warning Light System
  - System Pole Assembly
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- Design Example: In-Roadway Warning Light System
  - Load Calculation (Active and Standby)
    - Active Load → 10 Fixtures (250 ma/Fixture), 2 LED Edge Lit Signs (100 ma/Sign), 2 Push Buttons (10 ma/Push Button), 1 System Controller (50 ma) = **2.8 A (Approximately)**

    - Standby Load → 10 Fixtures (0), 2 LED Edge Lit Signs (0), 2 Push Buttons (1 ma/Push Button), 1 System Controller (25 ma) = **0.03 A (Approximately)**
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- **Design Example: In-Roadway Warning Light System**
  - **Usage Estimation:** 340 Crossings/Day @ 30 Sec/Crossing = 175 Min/Day = **3 Hours/Day (Approximately)**

<table>
<thead>
<tr>
<th>Usage</th>
<th>High</th>
<th>Med</th>
<th>Low</th>
</tr>
</thead>
<tbody>
<tr>
<td>Times</td>
<td>6-9, 4-7</td>
<td>9-4</td>
<td>7-6</td>
</tr>
<tr>
<td>Hours</td>
<td>6</td>
<td>7</td>
<td>11</td>
</tr>
<tr>
<td>Crossings</td>
<td>30/hour</td>
<td>15/hour</td>
<td>5/hour</td>
</tr>
<tr>
<td>Total Crossings</td>
<td>180</td>
<td>105</td>
<td>55</td>
</tr>
</tbody>
</table>

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340 Crossings/Day
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- Design Example: In-Roadway Warning Light System
  - Energy Usage Calculation
    - Note: All Lights Flash with a 50% Duty Cycle
    - Active Hours (3) x 50% Duty Cycle = 1.5 Effective Active Hours
      
      Effective Active Hours x Active Load = 1.5 x 2.8 = 4.2 Amp-Hours
    
    - Inactive Hours = (21) + (1.5 from above) = 22.5 Effective Standby Hours
      
      Effective Inactive Hours x Inactive Load = 22.5 x 0.03 = 0.7 Amp-Hours (Approximately)
    
    - Total Energy Usage/Day (Average) = 4.2 + 0.7 = 4.9 Amp-Hours/Day
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- **Design Example: In-Roadway Warning Light System**
  - **How much Energy is Available at the Site?**
    - Available Sun Energy (Insolation) = Site’s Insolation (Available in a Database and Expressed in Terms of Sun Hours), Modified (Reduced) by the Effects of Shading, If Present
    - A Solar Site Survey is Required to Determine if Shading is Present at the Site
  - **How do you Conduct a Solar Site Survey?**
    - Consists of a Series of Measurements of the Elevation Angle from the Panel Location to the Top of Potential Obstructions, and the Distance to the Potential Obstructions.
    - Measurements are made Along the Azimuth, Starting from True South and Extending +, - 90°, at 15° Intervals (1 Sun Hour) from True South.

<table>
<thead>
<tr>
<th>Solar Panel Location</th>
<th>Top of Obstacle</th>
</tr>
</thead>
<tbody>
<tr>
<td>d = Distance to Obstacle</td>
<td>Θ = Elevation Angle</td>
</tr>
</tbody>
</table>

**Note:** The Elevation Angle will need to be corrected for the measuring height and height of the panel!
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- Design Example: In-Roadway Warning Light System
  - How do you Determine True South?
    - To Determine **True South** you will need to know the **Magnetic Declination (D)**
    - Magnetic Declination is the Angular Amount that True North deviates from Magnetic North
    - From the Zip Code of the Site (76701) you can look up the Site’s Latitude and Longitude and Magnetic Declination. **Latitude** = 31.551955 North, **Longitude** = 97.13833 West, **Magnetic Declination** = 4° East (East is Negative)
    - **True South = 180° +  D for WACO**  **True South = 176° (As Indicated on a Magnetic Compass)**
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- Design Example: In-Roadway Warning Light System
  - Solar Plots
    - Next, To Determine if there are Shading Issues, Plot the Results of the Site Survey on a Solar Plot for the Site Location to determine the Effects of Obstacles on Insolation (Sun's Energy) Contributions
    - If the Elevation Angle of a Potential Obstacle is above the Elevation Angle of the Sun, then the Obstacle will Block the Sun — Shading — and the Relative Percentage of Available Energy Reduction will need to be Estimated
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- Design Example: In-Roadway Warning Light System
  - System Performance Criteria
      - Greater than 5 Days
    - **Array-to-Load Ratio (ALR)** – Measure of System’s Ability to Recover (Charge the Storage Battery) After a Period of High Activity, or Lower Than Average Insolation (Sun Energy)
      - Greater than 1.1
    - **Battery State of Charge (BSOC)** – Percentage of Charge (Energy Capacity) Available in the Battery. Limiting the Depth of Discharge (Maintaining a Higher State of Charge) Extends the Useful Life of Battery and Reduces Maintenance Costs
      - Greater than 80%
    - **Loss-of-Load Probability (LOLP)** - Probability of a Load Disconnect (System Switch-off) due to a Low Battery Charge Condition Caused by Extended Periods of Poor Weather
      - Less than 0.1 %
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- Design Example: In-Roadway Warning Light System
  - Balancing Energy Input and Output
  - Energy Input = Energy Storage + Energy Output to meet Performance Requirements

![Energy Flow Diagram]

- Energy Input
- Energy Flow Control
- Energy Output
- Energy Storage
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- **Effects of Environmental Conditions and Component Limitations on System Performance**
  - **Temperature Effects**
    - Solar Panel - Higher Temperature (Lower Power Output)
  - **Component Aging Effects**
    - Solar Panel – Power Output Decreases with Age
    - Storage Battery – Battery Capacity Decreases with Age
  - **Weather Conditions**
    - Air Moisture (Rain/Fog) Reduces Solar Insolation (Greater Absorption of Light) and Lowers Irradiance Levels
  - **Air Quality Conditions**
    - Dust/Smog Reduces Solar Panel Power Output (Greater Scattering of Light) and Lowers Irradiance Levels
  - **Irradiance Levels and Shading (Soft and Hard)**
    - Effect Solar Panel Power Output - Greater Effect between 9am – 3pm (Solar Time)
      - Reduces the Amount of Solar Insolation Reaching Panels
      - Greater Shading (Lower Power Output)
  - **Battery Characteristics - Discharge Rate and Depth of Discharge**
    - Faster Discharge – Lower Battery Capacity
    - Greater Depth of Discharge – Shorter Service Life
    - Temperature Effects on Battery Capacity and Service Life
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- Solar Panels - Effects of Temperature on Panel I-V Curve and Power
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- Atmospheric Effects on Irradiance Levels

Diagram showing the percentage of light absorbed, scattered, and reaching the Earth through different atmospheric layers:

- Ozone 20 - 40 km: 2%
- Upper Dust Layer 15 - 25 km: 1%
- Air Molecules 0 - 30 km: 8%
- Water Vapour 0 - 3 km: 6%
- Lower Dust Layer 0 - 3 km: 1%
- Direct to Earth: 70%
- Scattered to Space: Total 3%
- Scattered to Earth: 7%
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- Solar Panels - Effects of Irradiance (Light Intensity) on Panel I-V Curve
  - Lowered Irradiance Levels Referred to as Soft Shading

![I-V Curve Diagram](image-url)
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- Solar Panels – Standard vs. Photovoltaic Test Conditions

PV Panels Tested Using STC (Standard Test Conditions), Uses 25°C (Cell)

More Realistic to use PTC (PV Test Conditions) for Evaluations, Uses 20°C (Ambient)

Note: PVC = 88% STC
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- Design Example: In-Roadway Warning Light System
  - Energy Input
    - Energy is generated by the solar panel (Conversion process)
    - Solar Panels are rated for a power output under standard conditions

![BP 365 I-V Curves](image)

<table>
<thead>
<tr>
<th>Electrical Characteristics</th>
<th>BP 365</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum power ($P_{max}$)</td>
<td>65W</td>
</tr>
<tr>
<td>Voltage at $P_{max}$ ($V_{mp}$)</td>
<td>17.6V</td>
</tr>
<tr>
<td>Current at $P_{max}$ ($I_{max}$)</td>
<td>3.69A</td>
</tr>
<tr>
<td>Warranted minimum $P_{max}$</td>
<td>60W</td>
</tr>
<tr>
<td>Short-circuit current ($I_{sc}$)</td>
<td>3.99A</td>
</tr>
<tr>
<td>Open-circuit voltage ($V_{oc}$)</td>
<td>21.7V</td>
</tr>
<tr>
<td>Temperature coefficient of $I_{sc}$</td>
<td>$(0.065\pm0.015)%/\degree{C}$</td>
</tr>
<tr>
<td>Temperature coefficient of $V_{oc}$</td>
<td>$-(20\pm10)mV/\degree{C}$</td>
</tr>
<tr>
<td>Temperature coefficient of power</td>
<td>$-(0.5\pm0.05)%/\degree{C}$</td>
</tr>
<tr>
<td>NOCT (Air 20°C, Sun 0.8kW/m², wind 1m/s)</td>
<td>47.4°C</td>
</tr>
<tr>
<td>Maximum series fuse rating</td>
<td>20A</td>
</tr>
<tr>
<td>Maximum system voltage</td>
<td>600V (ETL &amp; IEC61215 rating)</td>
</tr>
</tbody>
</table>

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- **Insolation – Average Daily Solar Energy at a Site (Expressed in Sun Hours)**
  - **Peak Sun Hour**
    - Sun’s Available Power Varies During the Day
    - Available Energy (Insolation) is Power x Time
    - Standard Power of 1,000 Watts/Meter Squared is Used the Calculation (Solar Panels are Rated at this Level) to Covert the Unit of Energy to Peak Sun Hours (Sun Hours)
    - **Example - BP365:** \( P_m = 65 \text{ watts}, V_m = 17.6 \text{ Volts, } I_m = 3.69 \text{ Amps} \)
      - If Peak Sun Hours = 3, Then \( I_m \times \text{Sun Hours} = 3.69 \times 3 = 11 \text{ Amp-Hours (Approximately)} \)
    - **Note:** Solar Panel Sizing is Based on the Lowest Monthly Insolation for the Year (Lowest Energy Input) with Shading Effects Taken into Account
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- Solar Panels – Hard Shading Effects

Diagrams showing:
- Unshaded Cell: 100% current and voltage output
- Partially Shaded Cell: Output current directly proportional to illuminated area of cell. No voltage change
- Shaded Cell: No output possible

Legend:
- Rated Output
- Current Reduction
- Current & Voltage Reduction
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- Solar Panel Hard Shading Effects – Bypass Diodes

Bypass diodes across groups of solar cells. The voltage across the unshaded solar cells depends on the degree of shading of the poor cell. In the figure above, 0.5V is arbitrarily shown.
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- Solar Panel Shading Effects
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- Solar Panel Shading Effects
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- Solar Panel – Effects of Aging on Power Output

![% Power Output vs. Age Graph]

Typical Warranties
- 10 Year: 90% Output Power
- 25 Year: 80% Output Power
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- Battery Characteristics - Effect of Discharge Rate and Temperature on Battery Capacity
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- Battery Characteristics - Effects of Depth of Discharge and Temperature on Battery Service Life (80% Capacity)

Life Expectancy vs. Depth of Discharge

Note: @10%: 5,700 Cycles = 15.6 Years
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- **Design Example: In-Roadway Warning Light System**
  - **Design Problem**
    - **Given:**
      - Load Current and Energy Usage Requirements (Calculation)
      - Monthly Insolation (Data Base), Adjusted for Shading Effects (Measurement)
      - System Performance Requirements (Specified)
      - Knowledge of the Effects of Environmental and Component Factors
  - **Calculate:**
    - Solar Panel Size (Power and Current Capability)
    - Storage Battery Size (Energy Capacity)
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- **Design Process**
  - If Done Right, Is a Very Involved Process and Requires a Good Deal of Time
  - **Our Technique**
    - Assist Customer with Setting System Requirements and Site Survey
    - **Front End Software** → Used to Calculate the Load Current, Daily Energy Requirements, and Shading Energy Factors
    - **Back End Software** → Used to Take Into Account the Design Performance Requirements, Environmental Factors, and Component Limitations
  - **Result of the Process** → Sizing Report Used to document the Results of the Process that Certifies that a Proper Design Process has been Used and Specifies all Key Design Parameters and Solar Component Requirements
  - **Recommendation** → Always ask for a “Sizing Report” when Ordering a Solar Powered System

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- Sizing Report Summary

![Diagram showing solar powered warning light system design with data on system type, tracking, tilt, azimuth, PV modules, and battery Ah.](image-url)
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- Sizing Report – Array to Load Ratio
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- Sizing Report – Loss Of Load Probability
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- Sizing Report – Battery State of Charge
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- **System Installation Points**
  - **Pole Foundation Requirements**
    - Wind Loading, Soil Conditions, Local Codes
  - **Panel Orientation**
    - Orient in the True South Direction to Maximize Energy Generation
  - **Panel Tilt**
    - Optimize for Maximum Energy Generation in the Winter Months
  - **Panel and System Grounding**
    - Protection System from Lightning and Maintenance People from Electrical Shocks
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- System Installation Points
  - Pole Foundation Requirements

Note: Typical plans. Provided for Reference. Consult with a Civil Engineer regarding foundation details for your specific application. Foundations will vary depending on wind conditions, soil type, and items hung on the pole.
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- System Installation Points
  - Panel Orientation – Solar Panel Should be Mounted Facing True South for Maximum Performance

True South = 180° + Declination (East is Negative)

True South = 176° Magnetic
Solar Powered Warning Light System Design

- **System Installation Points**
  - Panel Tilt Angle – Solar Panel Should be Tilted

<table>
<thead>
<tr>
<th>SITE LATITUDE</th>
<th>NEAR OPTIMAL SOLAR PANEL TILT ANGLE (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 9</td>
<td>15</td>
</tr>
<tr>
<td>10 - 20</td>
<td>LATITUDE + 5</td>
</tr>
<tr>
<td>21 - 45</td>
<td>LATITUDE + 10</td>
</tr>
<tr>
<td>46 - 65</td>
<td>LATITUDE + 15</td>
</tr>
<tr>
<td>65 - 90</td>
<td>80</td>
</tr>
</tbody>
</table>

Waco, TX → Latitude = 31.5°
Tilt Angle = 31.5° + 10° = 40°
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- System Installation Points
  - Panel Grounding
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- Benefits of Solar Powered Systems
  - Allows Installation at Remote Sites
  - No Restoration Concerns or Expenses
  - Fast Deployment
  - Low Operating Costs
  - Equipment Costs are now Comparable to AC Powered Systems
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- Solar Power System Deployment Limitations
  - Areas of Low Insolation
  - High Wind Areas
  - Architectural Compatibility Concerns
  - Future Environmental Concerns
  - Large Obstructions (Buildings)
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Traffic Safety Corporation
Website: www.xwalk.com

Ted Vaeches
Marketing Manager

Office Phone: 888-446-9255

Cell Phone: 916-267-1008

Email: Ted.Vaeches@xwalk.com