Coupled Thermal-Electrical Modeling of Integrated Photovoltaic Systems

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Outline

• Introduction
• Methods
• Examples
  • Residential Rooftop PV
  • Evaluating the Energy Production of Vehicle-Integrated Photovoltaics (VIPVs)
  • Electric Vehicle Energy Consumption with On-board PVs
Introduction
PV Industry Background

• Solar power the fastest growing renewable energy source
• U.S. solar power capacity has experienced an average annual growth rate of 33% in the last decade [1]
• Global market of $160 billion in 2021 [2]
PV System Modeling

PV Performance Modeling Steps

1. Irradiance and Weather – Available sunlight, temperature, and wind speed all affect PV performance. Data sources include typical years (TMY), satellite, and ground measurements.

2. Incidence Irradiance – Translation of irradiance to the plane of array. Includes effects of orientation and tracking, beam and diffuse irradiance, and ground surface reflections.

3. Shading and Soiling – Accounts for reductions in the light reaching the PV cell material.

4. Cell Temperature – Cell temperature is influenced by module materials, array mounting, incident irradiance, ambient air temperature, and wind speed and direction.

5. Module Output – Module output is described by the I-V curve, which varies as a function of irradiance, temperature, and cell material.

6. DC and Mismatch Losses – DC string and array I-V curves are affected by wiring losses and mismatch between series connected modules and parallel strings.

7. DC to DC Max Power Point Tracking – A portion of the available DC power from the array is lost due to inexact tracking of the maximum power point.

8. DC to AC Conversion – The conversion efficiency of the inverter can vary with power level and environmental conditions.

9. AC Losses – For large plants, there may be significant losses between the AC side of the inverter and the point of interconnection (e.g., transformer).

10. System Performance Over Time – Monitoring of plant output can help to identify system problems (e.g., failures, degradation).

From Hansen and Martin. SAND2015-6700 Technical Report
Why Consider PV Temperatures?

• Solar cell efficiency typically decreases with increasing temperature

• Performance is often rated at 25 °C, while cells in operation reach significantly higher temperatures

• Therefore, cell T is needed for accurate energy production prediction
Limitations of Empirical Cell Temperature Models

- Many PV simulation libraries/software include empirical models for cell temperature
- Often these are used with default coefficients which are provided by the library based on literature
- Large disagreement between models
Advantages of Heat-Transfer Solver for PV Modeling

- Improved accuracy of temperature predictions for solar modules, especially if they are integrated into structures (e.g., vehicles and buildings)
- Analysis of the impact of PVs on the structures’ temperatures
  - E.g.: How could cabin T and occupant comfort change if PV films are integrated into building windows or vehicle sunroof?
- Design of PV cooling techniques
PV Modeling with TAITherm
Coupled Thermal-Electrical Model

- PV electrical equations solved at end of each thermal simulation time-step
- Model inputs use information available from manufacturer datasheets
TAITherm Transparent Materials Modeling

- Specify transmittance and reflectance or each layer as band-averaged values or spectral curves in TAITherm
  - Curves will be band-averaged based on the solar spectrum

\[
\int_0^\infty d\lambda = \bar{T}
\]
PV Modeling Extension Prototype Demo
Example Application: Residential Rooftop PVs
Example Residential Rooftop PV Model
Residential Rooftop PV Model: Considering Soiling Losses

- Soiling loss can be split into a transmission and angular loss contribution

\[ L_{\text{trans}}^{\text{soiling}} = c(d_r^{\text{dirty}} - d_r^{\text{clean}})/100 \]

\[ L_{\text{tot}} = L_{\text{trans}}^{\text{soiling}} (1 - K_a) \]
Residential Rooftop PV Model: Considering Soiling Losses

![Graphs showing DC Power and Total DC Energy with and without soiling over months.](image)
Example Application: Evaluating the Energy Production of Vehicle-Integrated Photovoltaics (VIPVs)
Vehicle-Integrated Solar Panels

- Extend the range of electric vehicles
- Power an auxiliary battery for secondary electronics systems in both internal combustion engine and electric vehicles
Vehicle-Integrated Solar Panels

- Predicted 3.8 kWh of energy production per 8 hours in the sun in Phoenix, AZ in July
- 3% angular losses and 13% thermal losses
Wavelength-Selective Transparent PVs

• Absorb UV/IR wavelengths, while transmitting visible light

Fig. from Traverse et al. Nature Energy, 2017

Data from A. Antil et al. Appl. Energy, 2020

Potential of Vehicle-Integrated Transparent PVs

- Comparison of energy production for different levels of PV coverage on vehicle and different locations
- Realistic weather and irradiance for each location was taken from TMY data from NSRDB
VIPV Feasibility for HVAC

• Cooling energy needs of an HVAC system during moderate length trips could be entirely supplied by VIPV system

<table>
<thead>
<tr>
<th>Impact of Desired Vehicle Temperature on EV Energy Consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outside Temp</td>
</tr>
<tr>
<td>110 °F</td>
</tr>
<tr>
<td>110 °F</td>
</tr>
<tr>
<td>110 °F</td>
</tr>
</tbody>
</table>

Data is for an electrically driven heat pump. From https://avt.inl.gov/sites/default/files/pdf/fsev/auxiliary.pdf

<table>
<thead>
<tr>
<th>Modeled Energy Production after 8 hours on a sunny summer day in Phoenix, AZ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full TPV Coverage</td>
</tr>
<tr>
<td>Windows Only TPVs</td>
</tr>
<tr>
<td>Si PV Roof</td>
</tr>
</tbody>
</table>
Example Application:
Electric Vehicle Energy Consumption with On-board PVs
Approach Overview

Run TAI-Therm vehicle cabin model for drive cycles in different seasons

If thermal comfort (or cabin temperature) differs from HVAC setpoint, apply HVAC heating/cooling

HVAC power

Run 0D power consumption model

Inputs:
- BEV parameters
- Weather

Power consumption profiles

PV power

Motor Generator

Transmission

Wheels

Rolling resistance
Aerodynamic drag
Climbing / descending
Acceleration / rotational inertia

Battery

Heat pump
Heating resistor
Air conditioner

Heat source

PV Model
TAITherm Vehicle Modeling Steps

- Find garage temperature at start of commute
- Assume vehicle starts in thermal equilibrium with garage. Run SS on vehicle in bounding box set to garage temperature to set initial conditions.
- Transient restart into 40 min. morning commute, adding the driver to the vehicle. HVAC is regulated based on driver’s thermal comfort (PMV).
- Transient restart into parked car model. Car is parked in an unshaded area for ~8 hours.
- Transient restart into 40 min. afternoon commute, adding the driver to the vehicle. HVAC is regulated based on driver’s thermal comfort.

Time-series of HVAC power use and PV power generation
Predicted Mean Vote for HVAC Control

• A comfort metric developed by Fanger (and standardized by ISO7730)
• Predicts mean value of votes of large group of persons on a 7-point thermal sensation scale ranging from -3 (cold) to +3 (hot)
• Considers activity level, clothing resistance, air temperature, mean radiant temperature, air velocity, and relative humidity
• An output of the TAITherm Human Thermal Model
TAITherm Human Thermal Model

- 20 body segments, with layers representing tissues
- Solves bio-heat transfer equation
- Predicts tissue, blood, and core temperatures under:
  - Varying environmental conditions
  - Varying activity levels
  - Adjustable clothing levels

Mechanisms considered by TAITherm Human Thermal Model
Human Comfort for HVAC Power Consumption

- HVAC control algorithm implemented in a User Routine
- \( Q_{HVAC} = f(\text{PMV}, \frac{d(\text{PMV})}{dt}) \), \( v_{air} = f(\text{PMV}, \frac{d(\text{PMV})}{dt}) \)
EV Power Model Inputs

- EV parameters
- Drive cycle (speed time-series)
- Weather
- HVAC load and PV power from TAITherm cabin model

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>Curb Weight</td>
<td>3000 kg</td>
</tr>
<tr>
<td>Gear Ratio</td>
<td>8.0</td>
</tr>
<tr>
<td>Frontal Area</td>
<td>2.88 m²</td>
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<tr>
<td>Drag Coefficient</td>
<td>0.371</td>
</tr>
<tr>
<td>Max Power</td>
<td>220 kW (300 hp)</td>
</tr>
<tr>
<td>Battery Discharging Efficiency</td>
<td>95%</td>
</tr>
<tr>
<td>Battery Charging Efficiency</td>
<td>90%</td>
</tr>
<tr>
<td>Transmission Efficiency</td>
<td>95%</td>
</tr>
<tr>
<td>HVAC Coefficient of Performance</td>
<td>2</td>
</tr>
<tr>
<td>Auxiliary Power</td>
<td>0.3 kW</td>
</tr>
</tbody>
</table>
EV Power Model Outputs

- Total power load time-series
- Power loads and losses from individual components of EV

[Graphs showing City Drive Cycle and Highway Drive Cycle Calculated Power Load]
Case Study

• Modeled EV energy balance over 1 day for 2 drive cycles in each of 4 seasons in Phoenix, Arizona and Detroit, Michigan
  • 40 min morning commute + 8 hours parked outside + 40 min afternoon commute
• VIPVs generate 10-23% and 3-8% of consumption (or 4-11 km of range) of city and highway drive cycles, respectively

Results: Phoenix, Arizona
Results: Detroit, Michigan

- VIPVs generate 5-19% and 2-7% of consumption (or 2-9 km of range) of city and highway drive cycles, respectively
Results: Impact on HVAC Load

- HVAC load significantly reduced in cooldown scenarios due to VIPV’s converting some of solar radiation to electricity instead of heat.
Conclusions

- We demonstrated how TAITherm could be used for EV energy consumption with consideration of VIPVs and HVAC loads
- For a full size SUV, with non-optimized aerodynamics (0.371 drag coeff.), amount of range extension expected from integration of conventional solar cells into the roof and hood is 2-11 km per day
  - More aerodynamic or lighter weight vehicles would get more range from VIPVs
  - ~3x more energy could be gained by achieving full vehicle coverage
Future Work

- PV thermal-electrical model and EV energy model could be coupled with thermal-electrical battery performance and lifetime models for more detailed analysis.

Potential Future Modeling Approach

Environmental Conditions
- Irradiance (GHI, DNI, DHI)
- Wind speed
- Temperature
- Soiling

Power Generation profile

Environmental Conditions
- Ambient Temperature
- Wind speed
- Solar Loading

Battery stress statistics
- T(t), V(t), ΔSOC(t), ...

PV System Design Parameters
- DC/AC Rating
- Tilt and Azimuth Angle
- Cell Type

Battery Management System Model

Thermal/Electric Battery Model

NREL Battery Lifetime Model
References

1. https://www.seia.org/solar-industry-research-data
Thank you

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