Coupled Thermal-Electrical Modeling of Integrated Photovoltaic Systems

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THERMO ANALYTICS

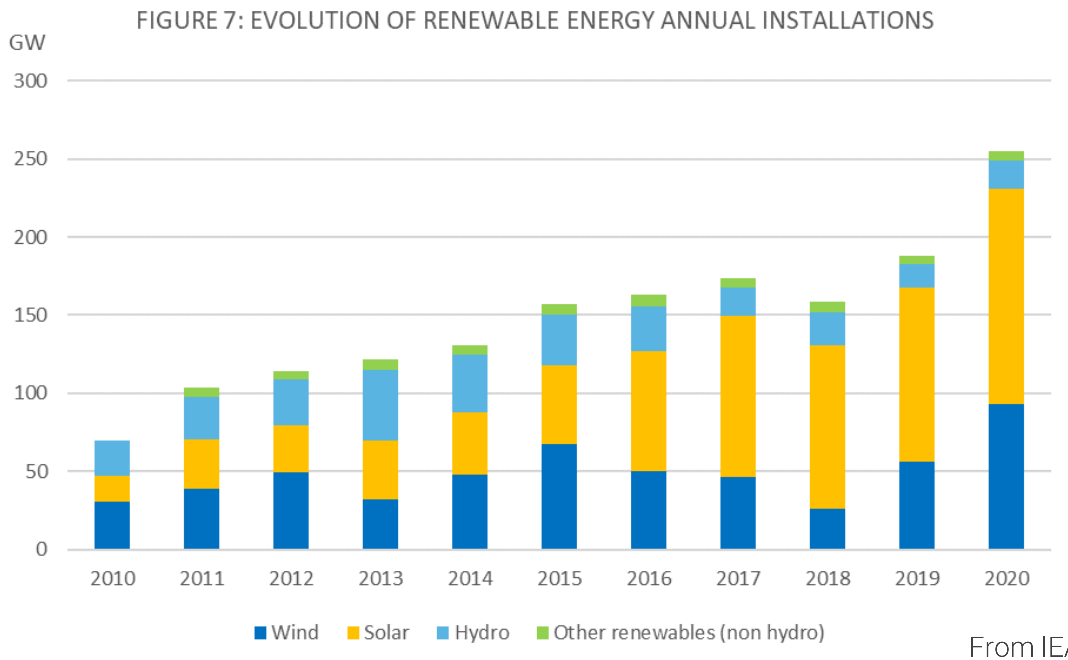
Outline

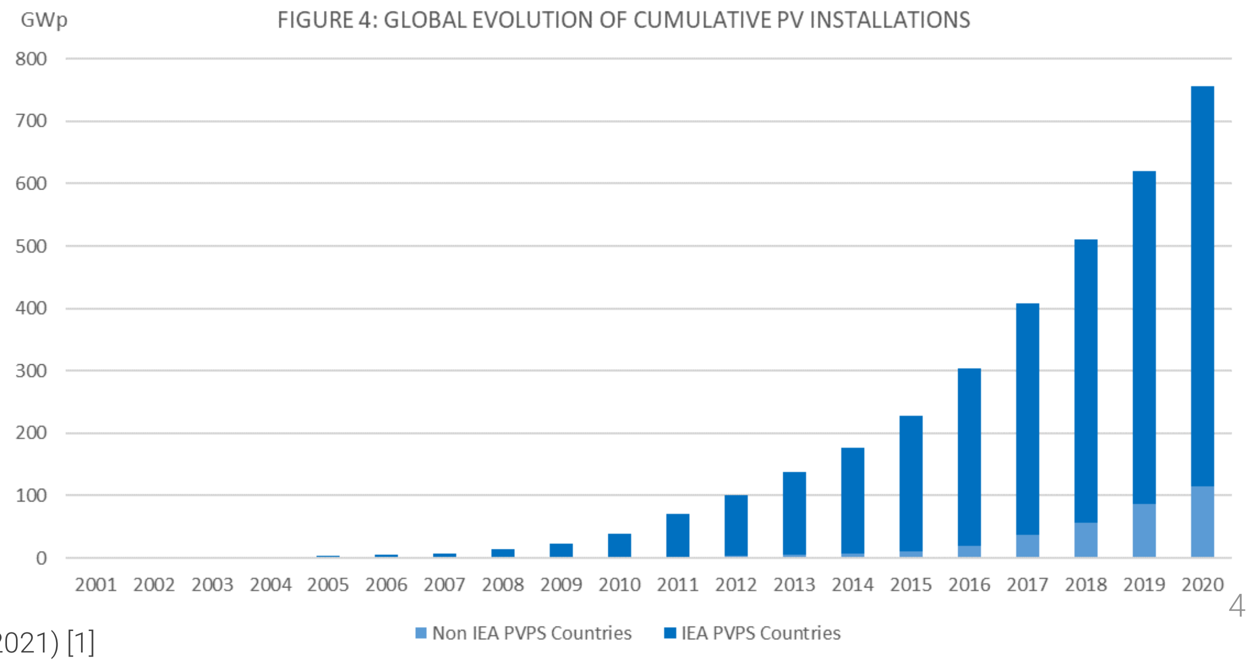
- Introduction
- Methods
- Examples
  - Residential Rooftop PV
  - Evaluating the Energy Production of Vehicle-Integrated Photovoltaics (VIPVs)
  - Electric Vehicle Energy Consumption with On-board PVs

Introduction

PV Industry Background

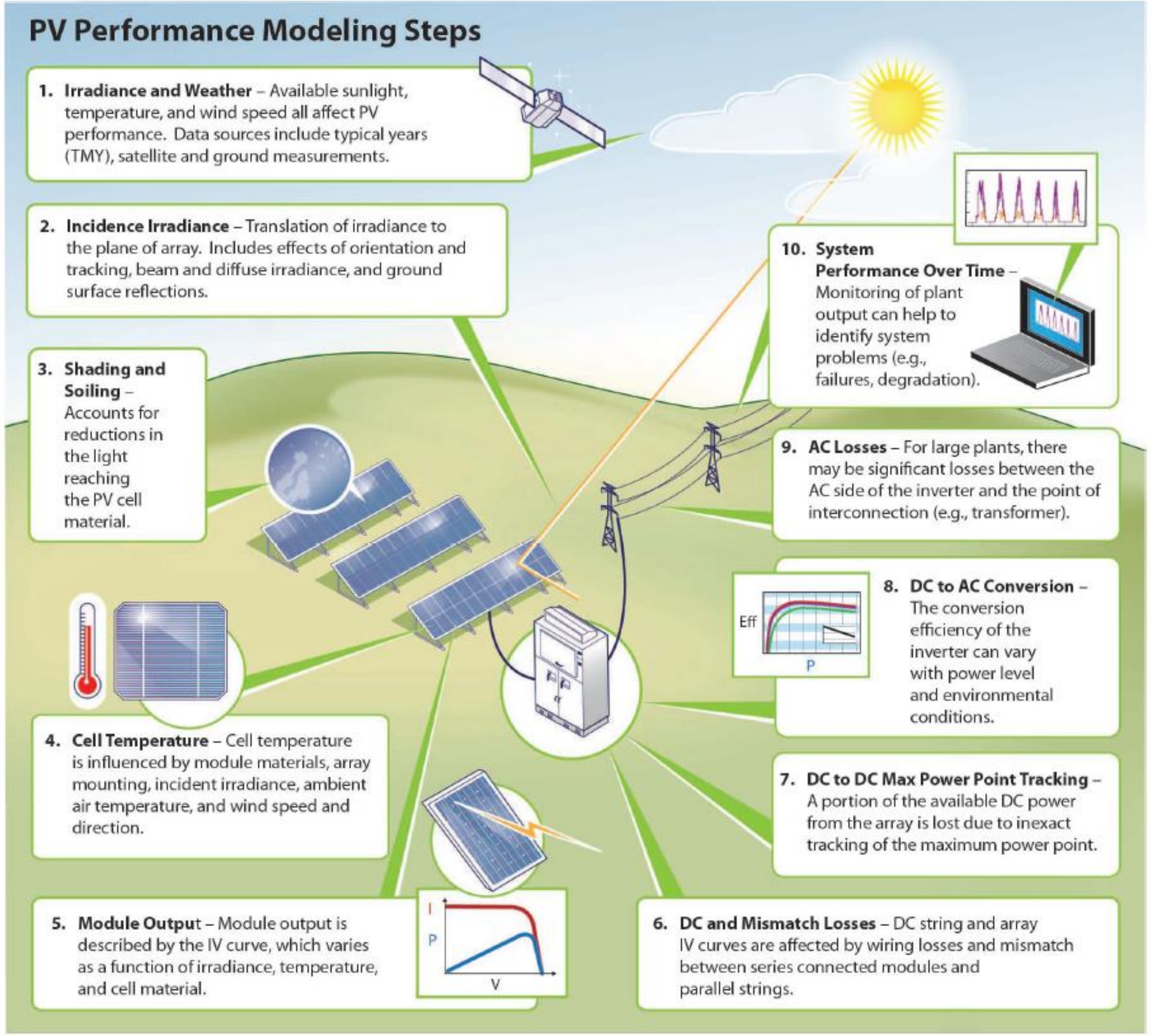
- Solar power the fastest growing renewable energy source
- U.S. solar power capacity has experienced an average annual growth rate of 33% in the last decade [1]
- Global market of $160 billion in 2021 [2]





From IEA (2021) [1]

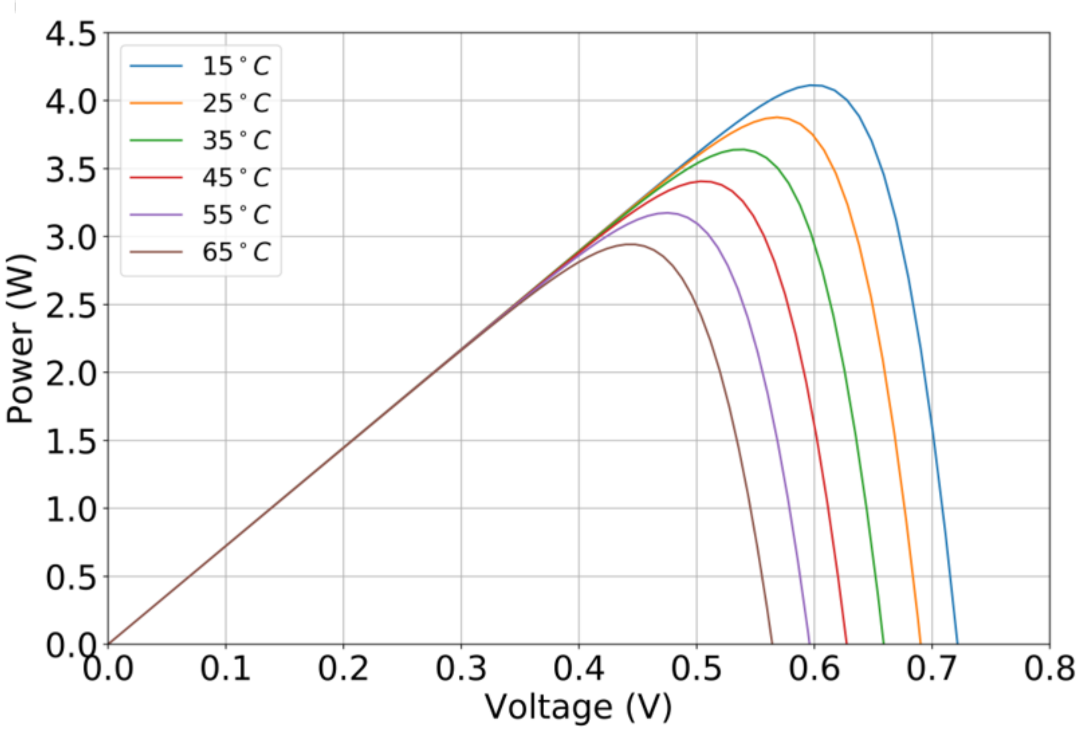
PV System Modeling



From Hansen and Martin. SAND2015-6700 Technical Report

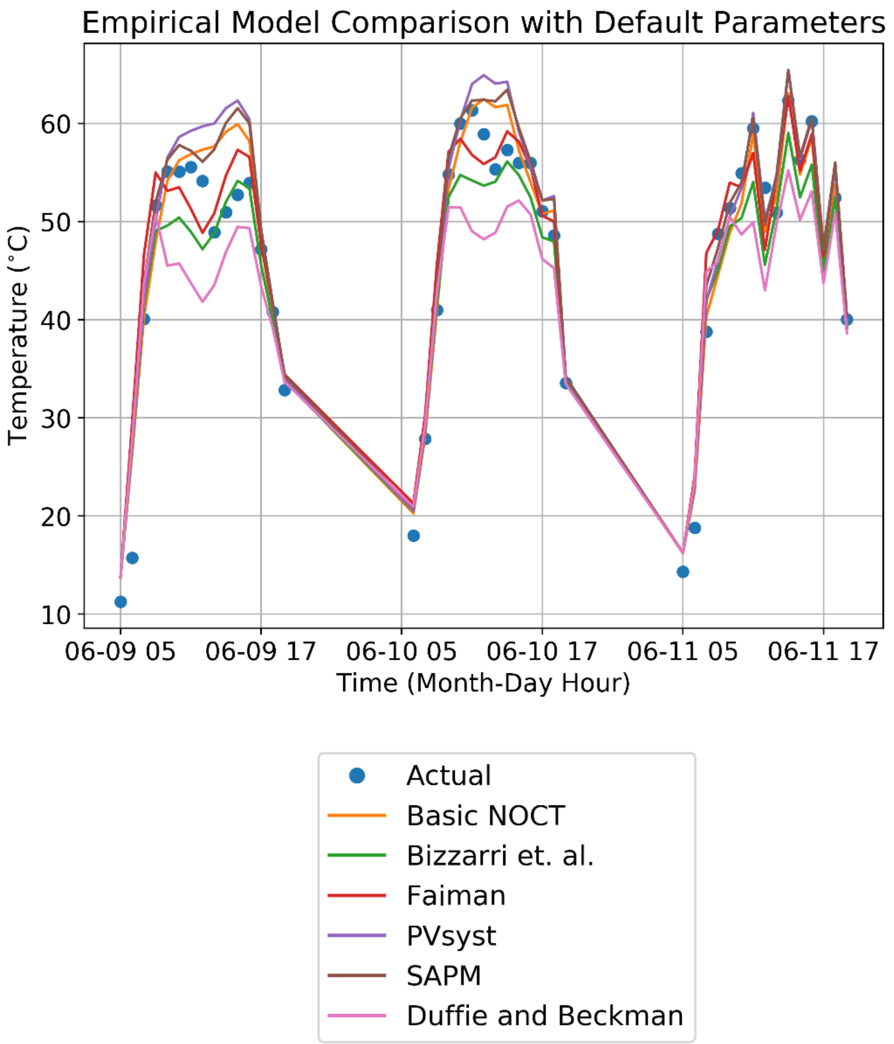
Why Consider PV Temperatures?

- 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



[3]

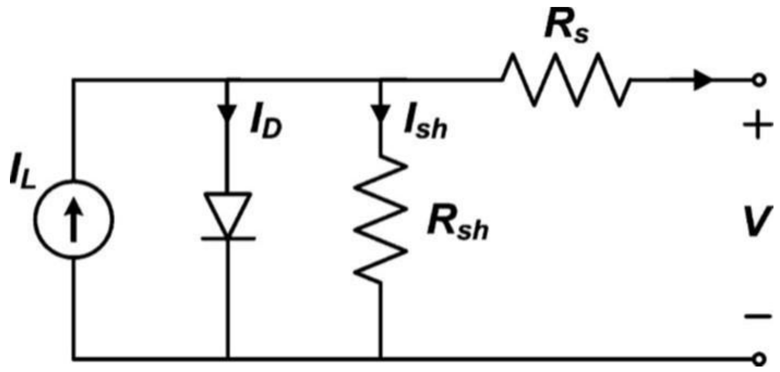
Advantages of Heat-Transfer Solver for PV Modeling

- Improved accuracy of temperature predictions for solar modules, especially if that 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

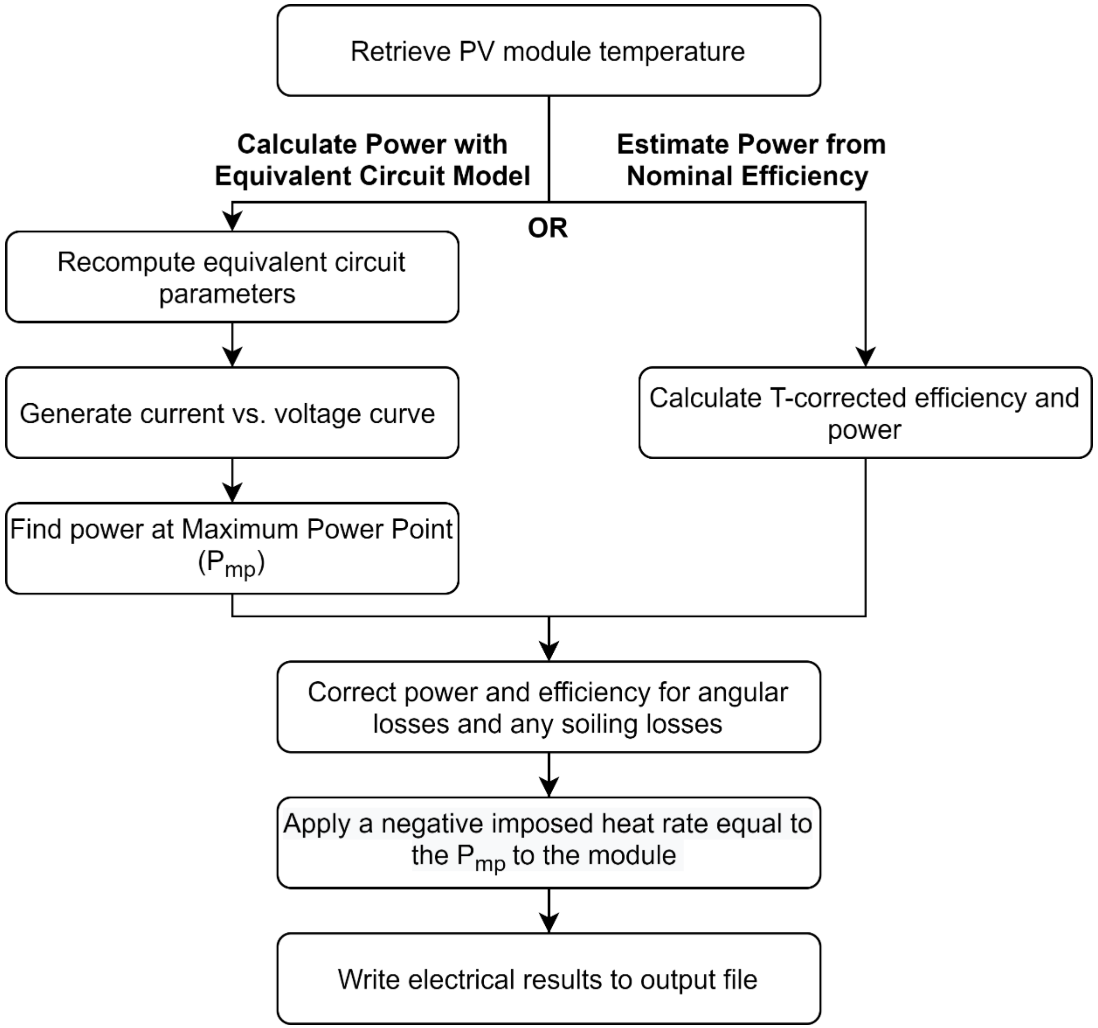
PV Modeling with TAITherm

Coupled Thermal-Electrical Model

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



$$I(V) = I_L - I_0(e^{(V+IR_s)/a} - 1) - \frac{V + IR_s}{R_{sh}}$$



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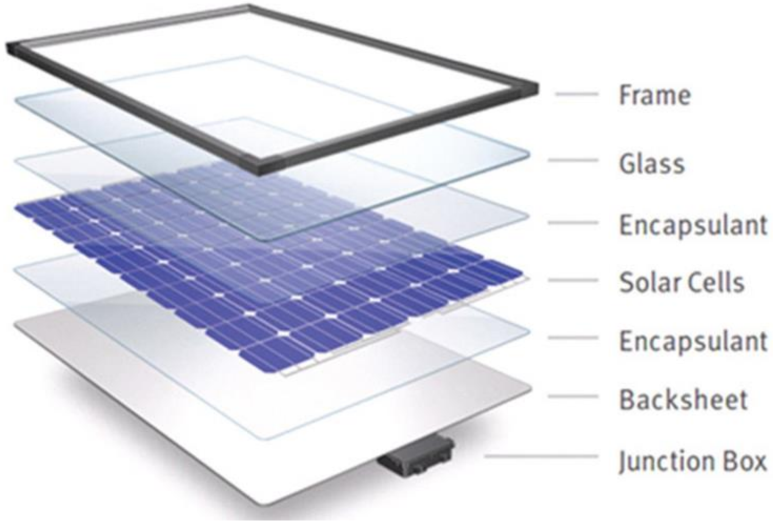
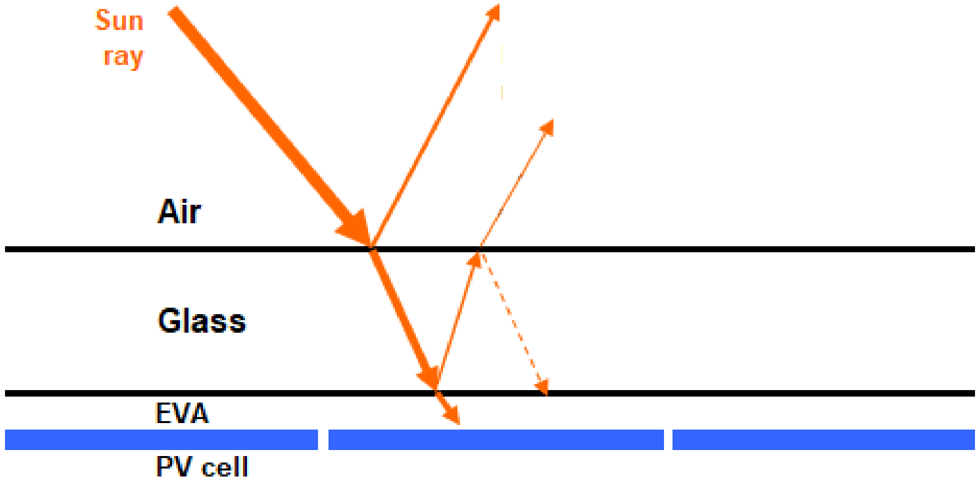
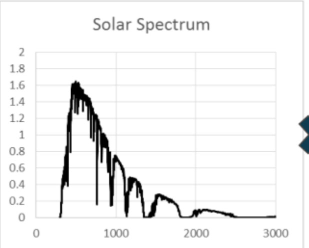
TAITherm Transparent Materials Modeling





- 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

$$\int_0^\infty$$



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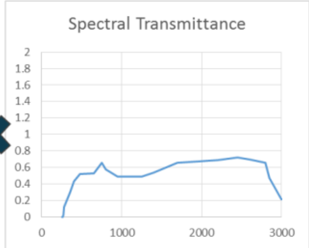
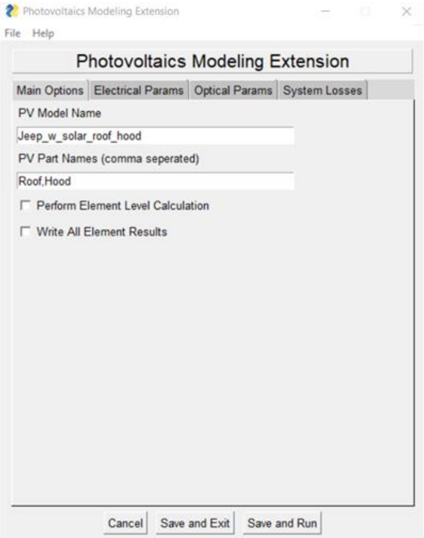
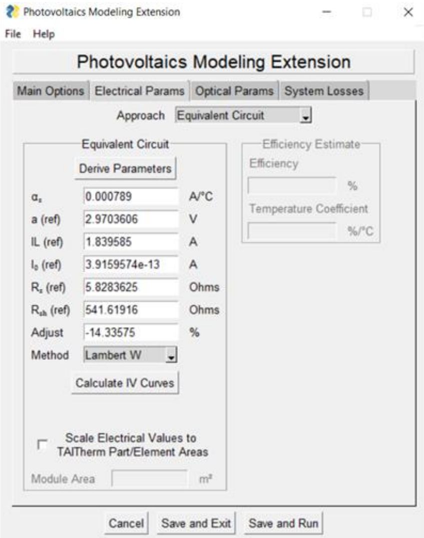
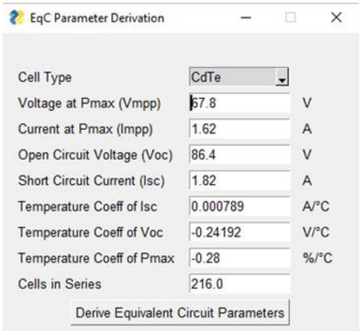


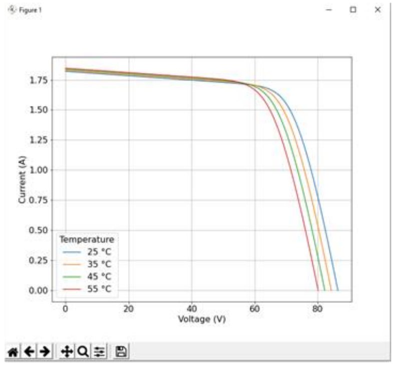
$$d\lambda = \bar{T}$$

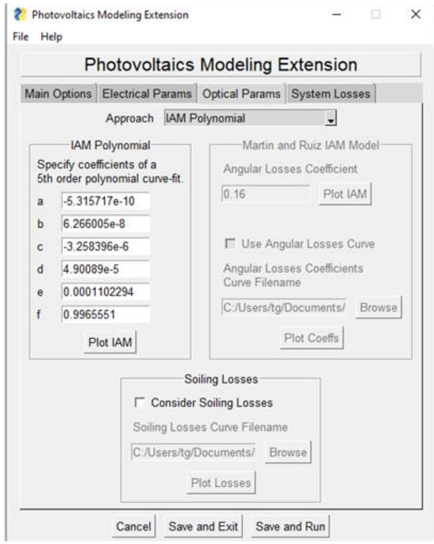
PV Modeling Extension Prototype Demo

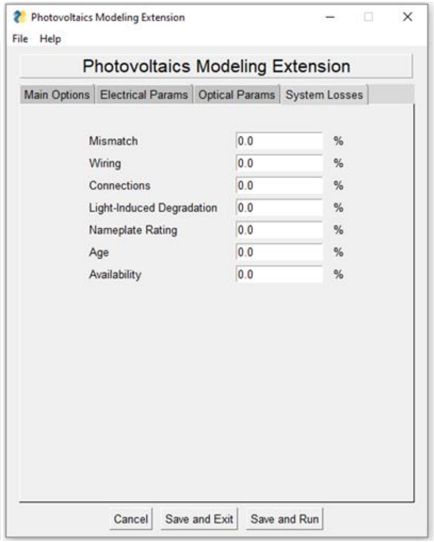


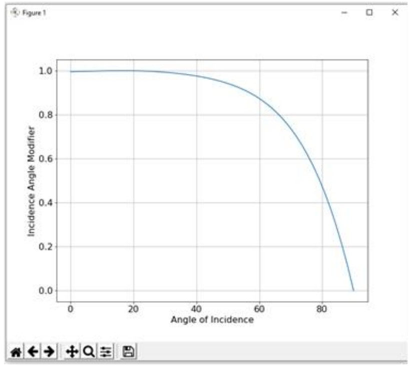


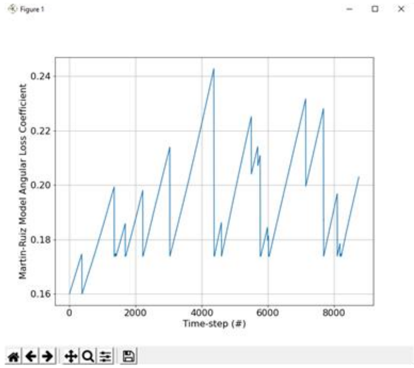








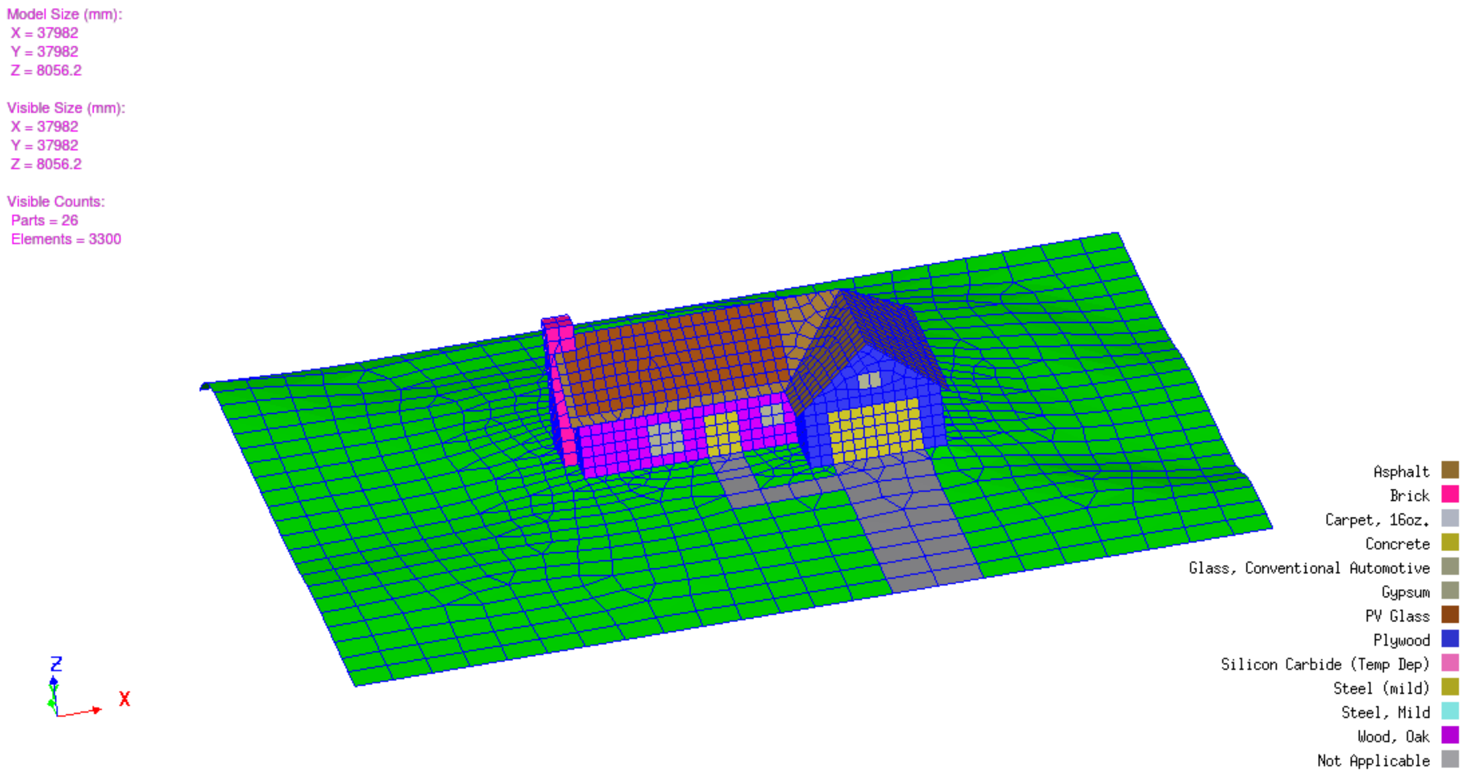


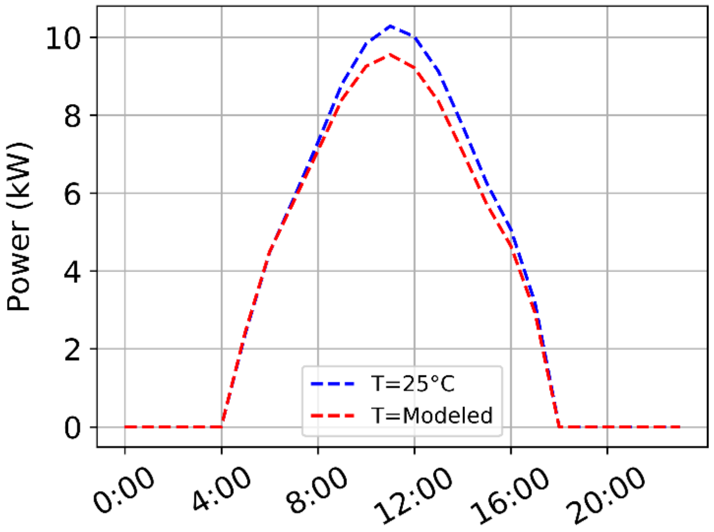


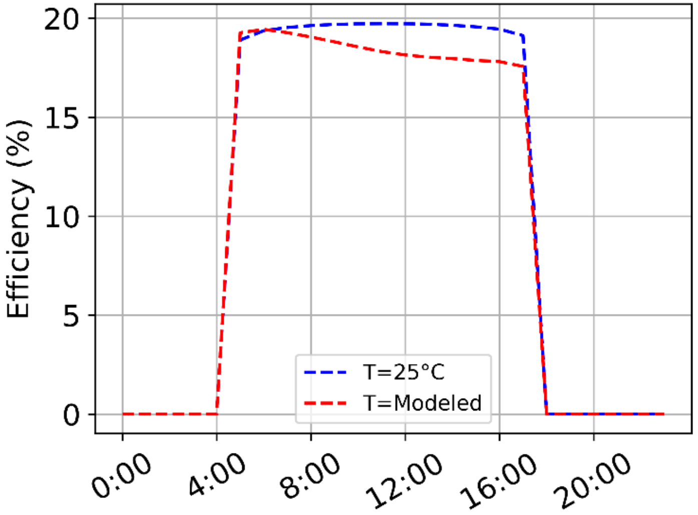
Example Application: Residential Rooftop PVs

[3]

Example Residential Rooftop PV Model



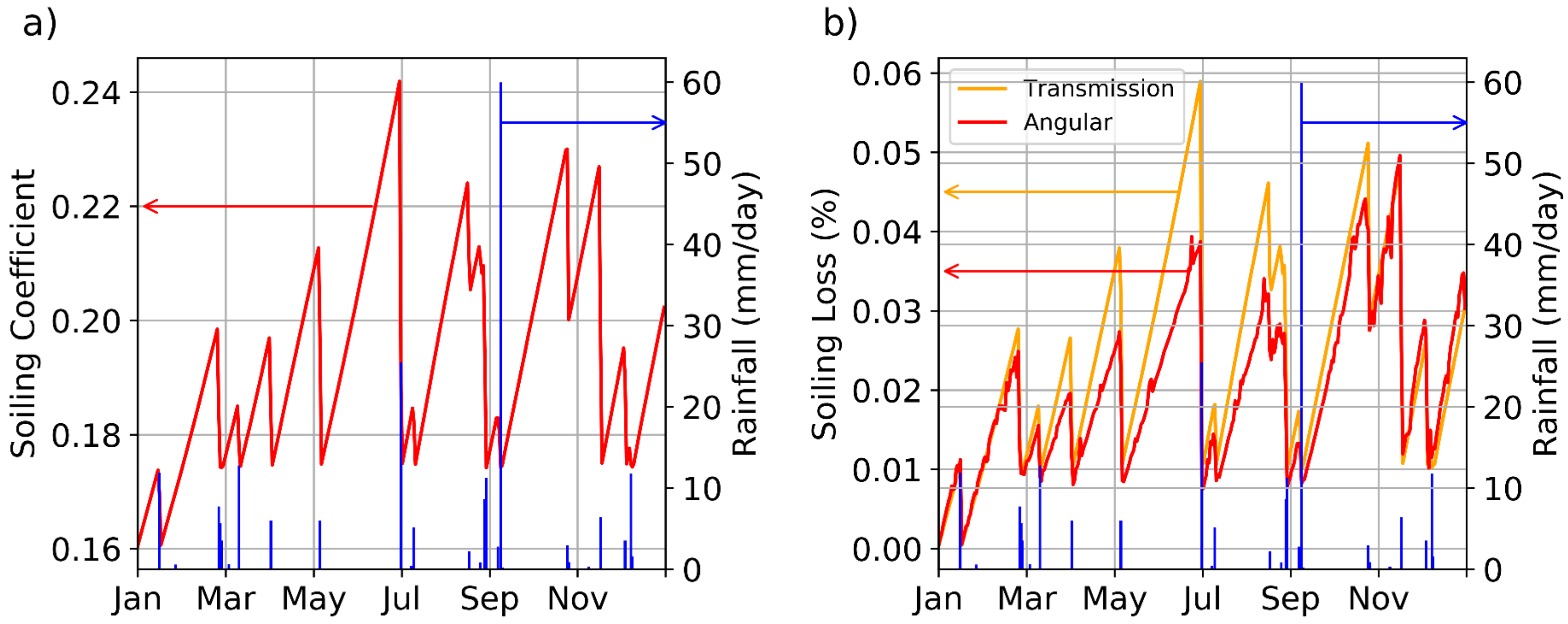




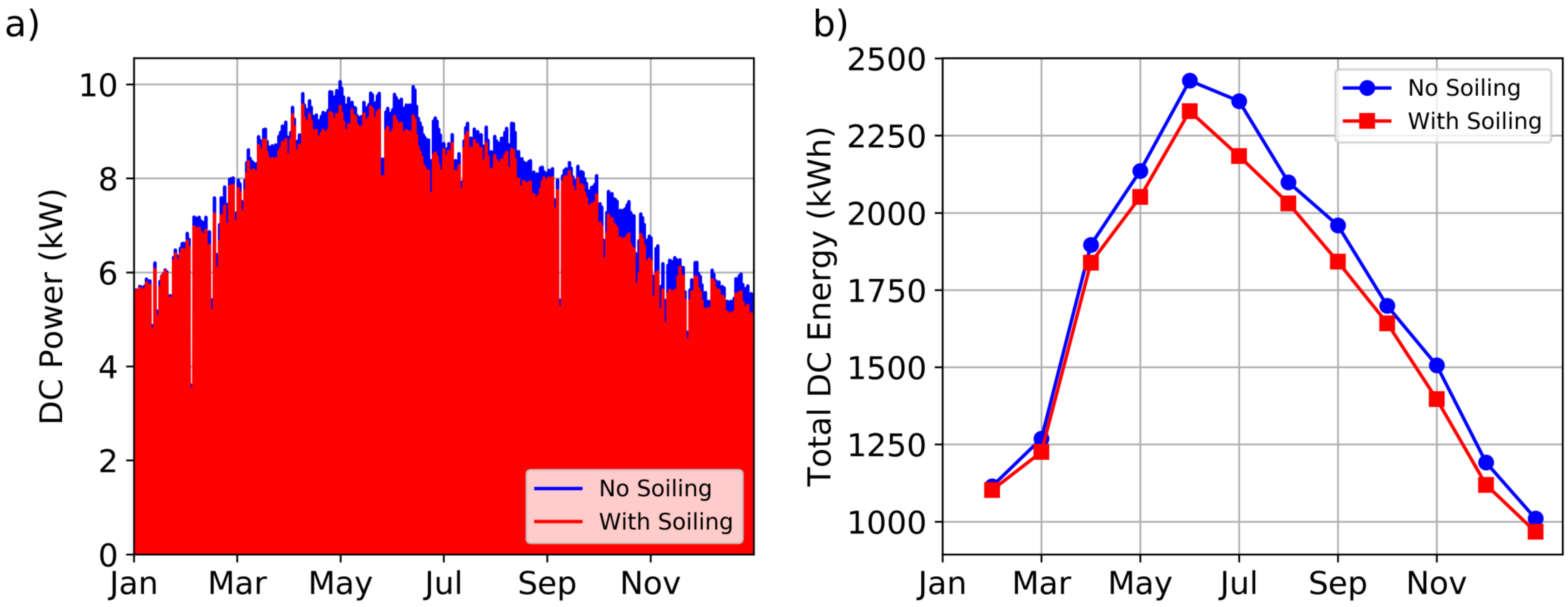
Residential Rooftop PV Model: Considering Soiling Losses

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

$$L_{trans}^{soiling} = c(a_r^{dirty} - a_r^{clean})/100 \qquad L_{tot} = L_{trans}^{soiling}(1 - K_\alpha)$$



Residential Rooftop PV Model: Considering Soiling Losses

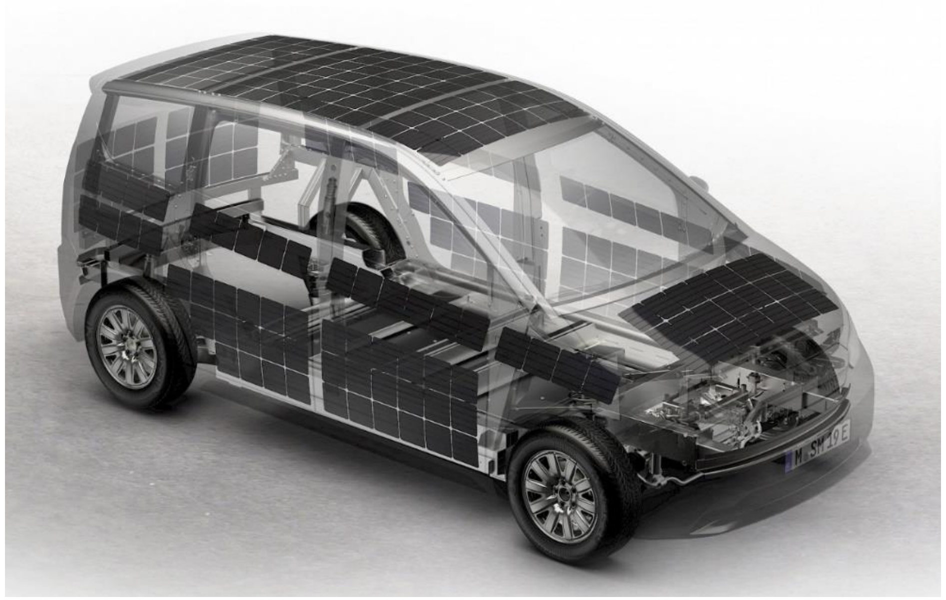


Example Application: Evaluating the Energy Production of Vehicle-Integrated Photovoltaics (VIPVs)

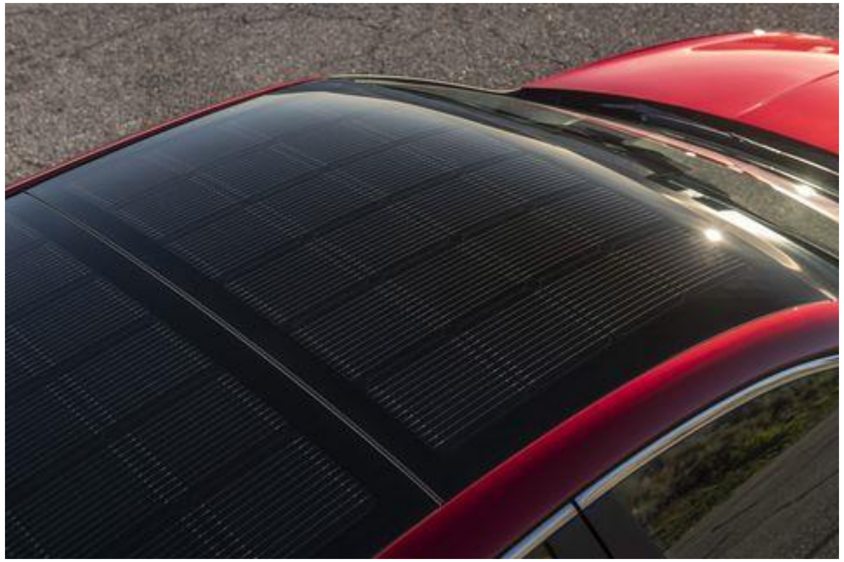
Vehicle-Integrated Solar Panels

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

Hyundai (2018). Translucent solar roof engineering.

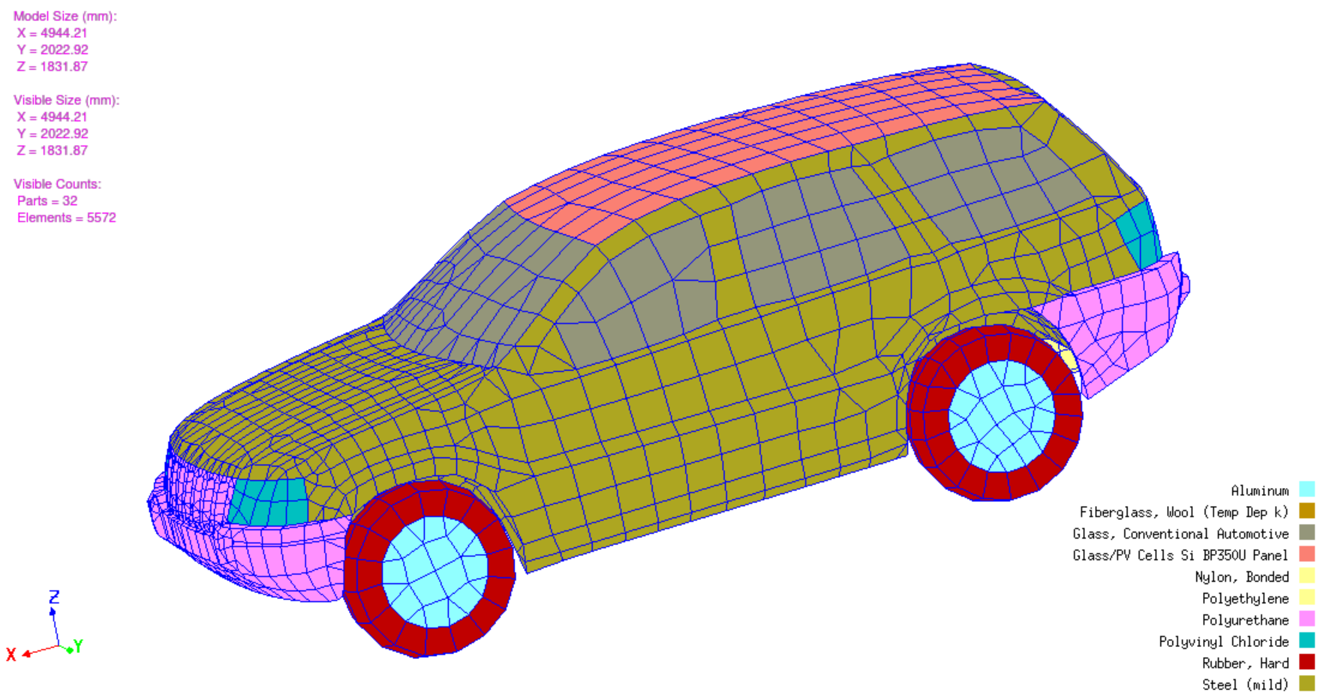


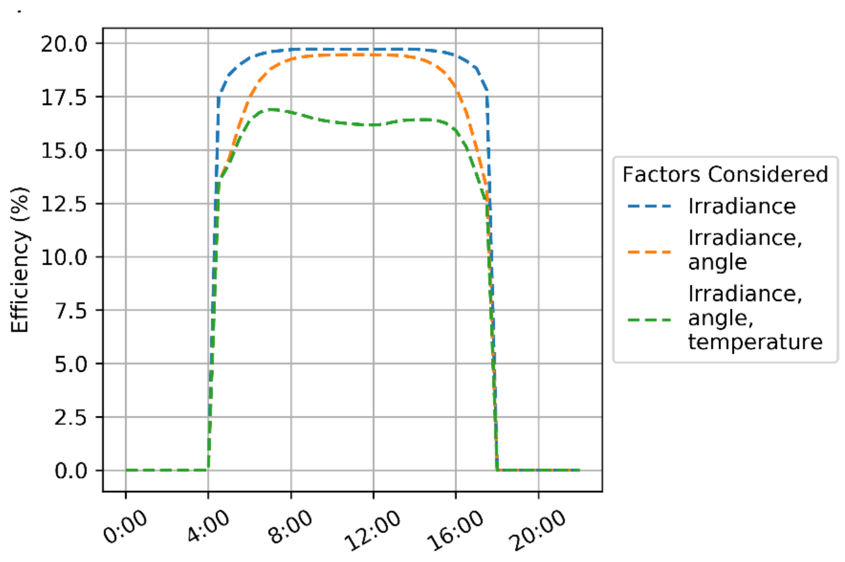
Sono Motors. Up to 34 km/day. Expected 2022. €25,500

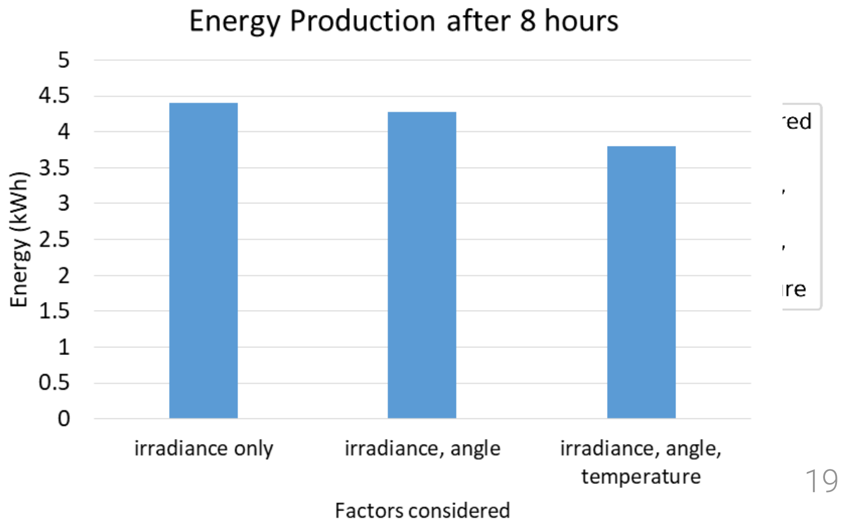


2020 Hyundai Sonata Hybrid

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

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Wavelength-Selective Transparent PVs

- Absorb UV/IR wavelengths, while transmitting visible light

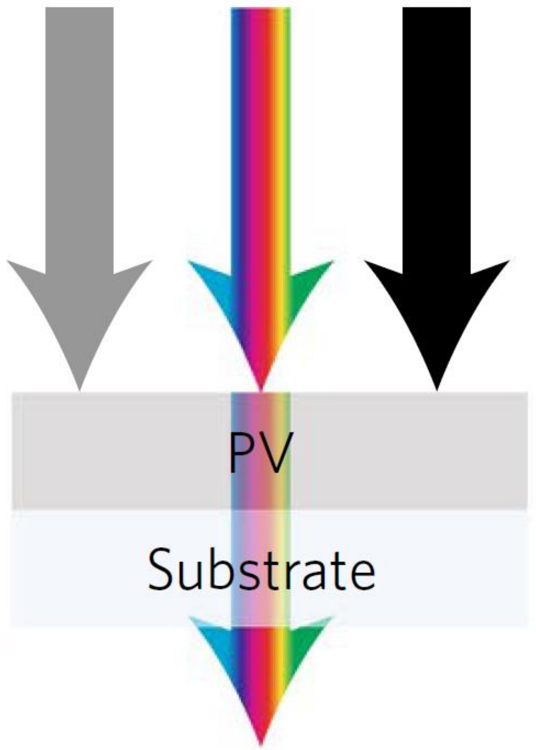
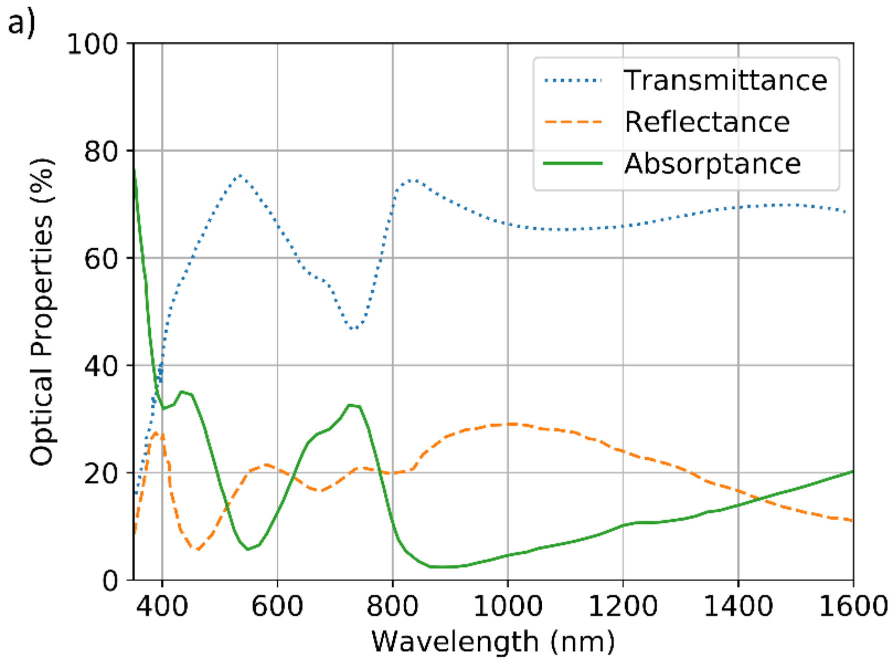
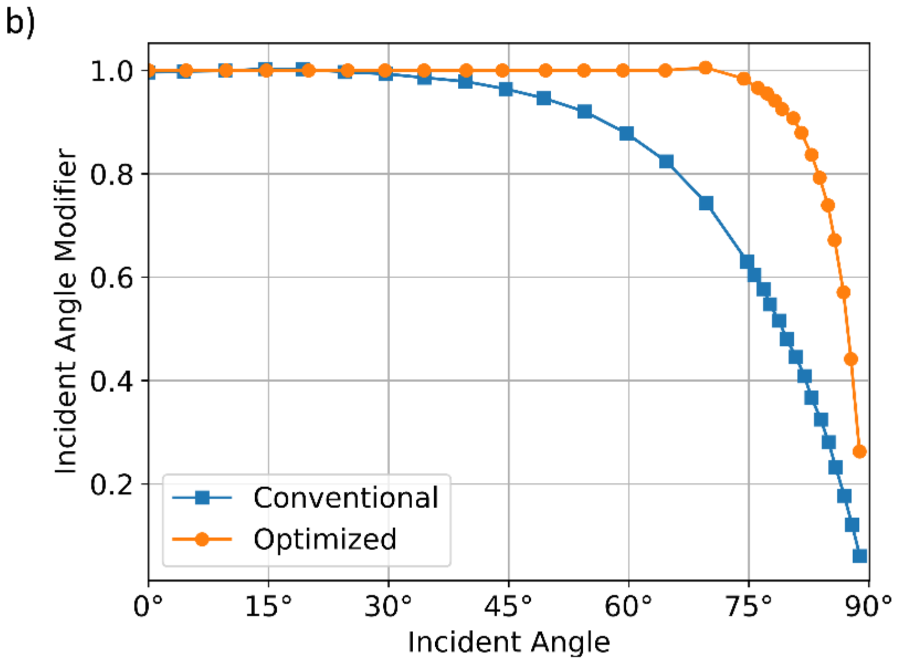


Fig. from Traverse et al. Nature Energy, 2017



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

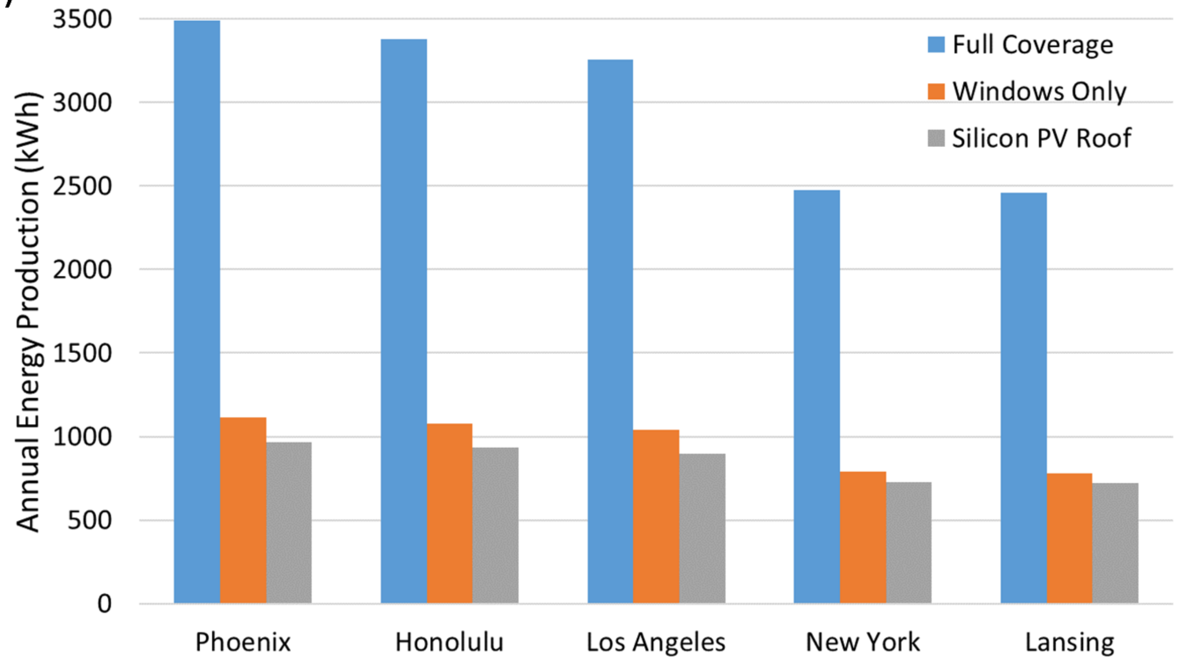


Data from Y. Ding et al. Sol. Energy Mater. Sol. Cells, 2015

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

a)



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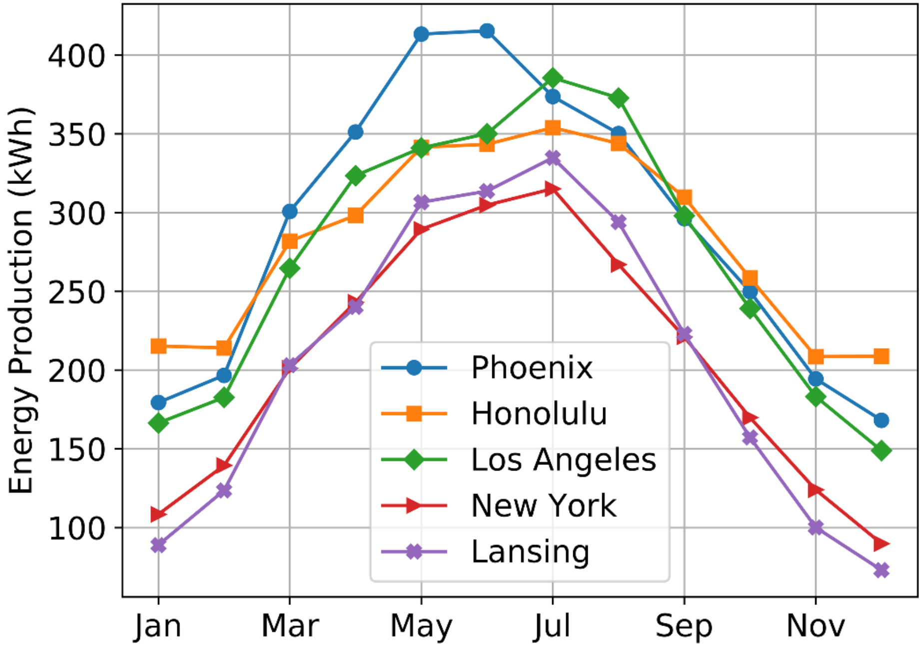


[3, 4]

VIPV Feasibility for HVAC

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

Impact of Desired Vehicle Temperature on EV Energy Consumption		
Outside Temp	Desired Vehicle Temp	Energy Consumption
110 °F	70 °F	1.5-2 kW
110 °F	77 °F	1 kW
110 °F	84 °F	0.5 kW

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

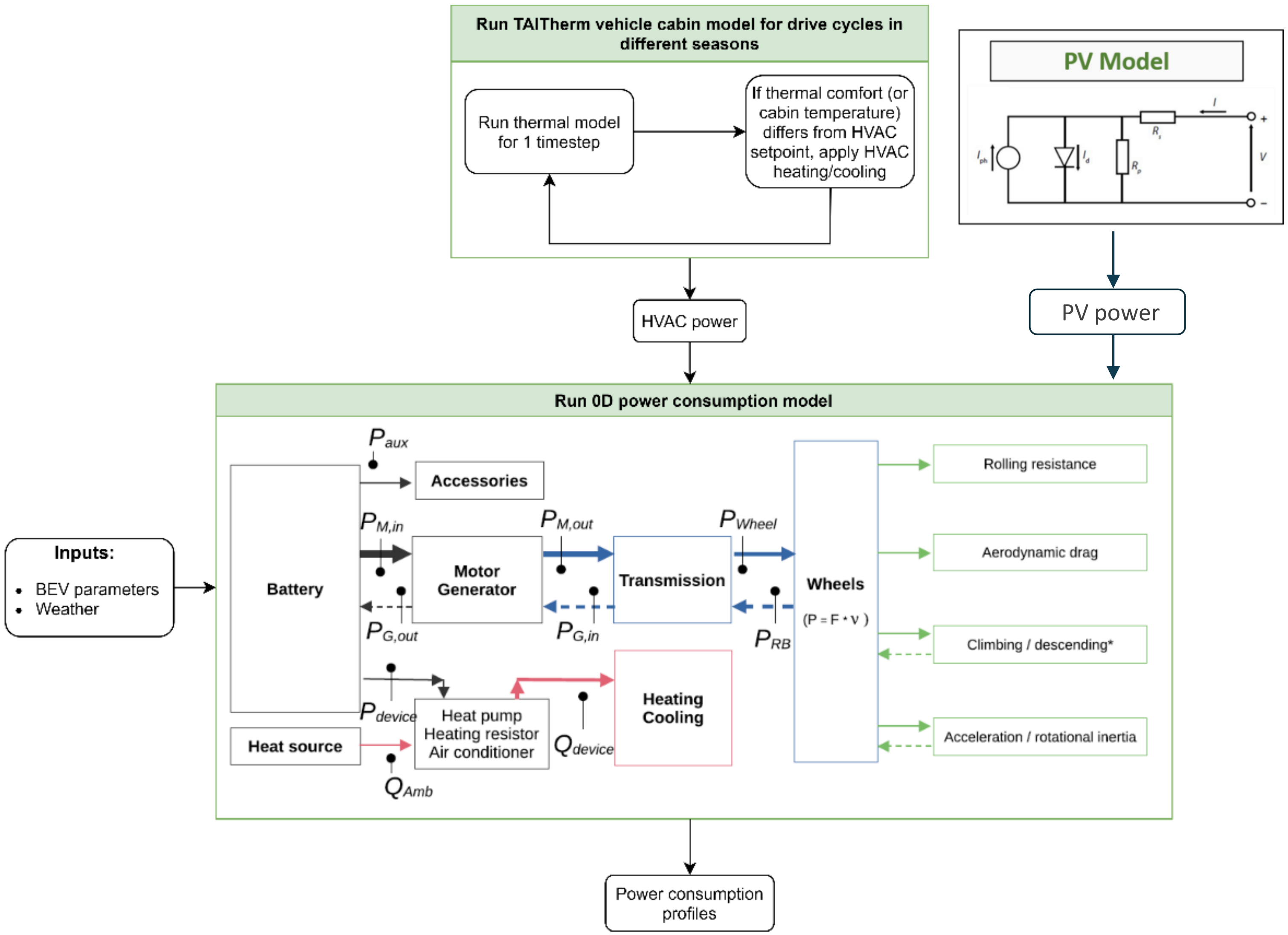
Modeled Energy Production after 8 hours on a sunny summer day in Phoenix, AZ	
Full TPV Coverage	13.8 kWh
Windows Only TPVs	4.5 kWh
Si PV Roof	3.8 kWh

Example Application:

Electric Vehicle Energy Consumption with On-board PVs

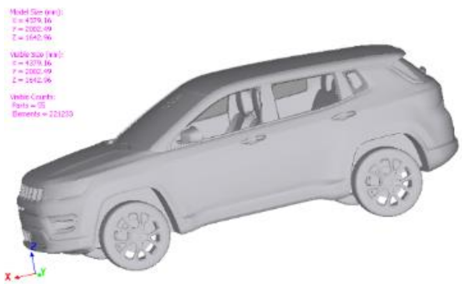
[5]

Approach Overview

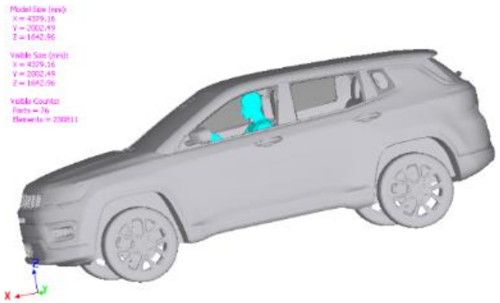


TAITherm Vehicle Modeling Steps

Find garage temperature at start of commute

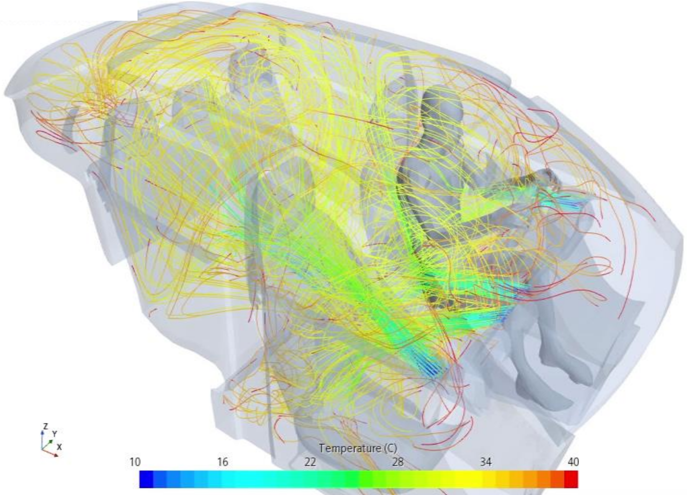


Assume vehicle starts in thermal equilibrium with garage. Run SS on vehicle in bounding box set to garage temperature to set initial conditions.

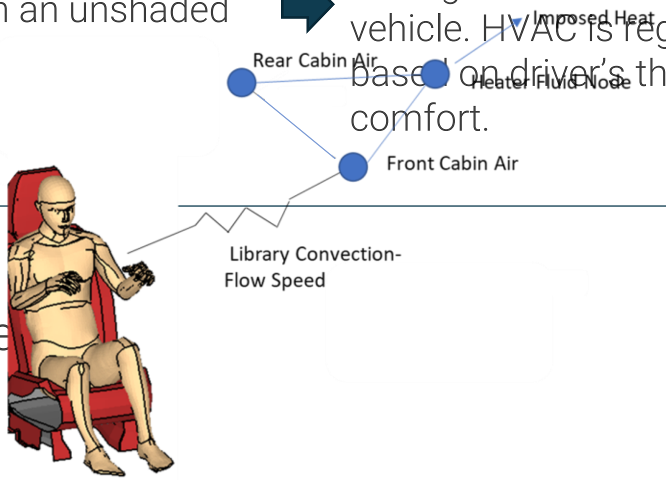


Transient restart into 40 min. morning commute, adding the driver to the vehicle. HVAC is regulated based on driver's thermal comfort (PMV).

Transient restart into parked car model. Car is parked in an unshaded area for



ransient restart into 40 in. afternoon commute, adding the driver to the vehicle. HVAC is regulated base on driver's thermal comfort.



Time-series of HVAC power use and PV power gene

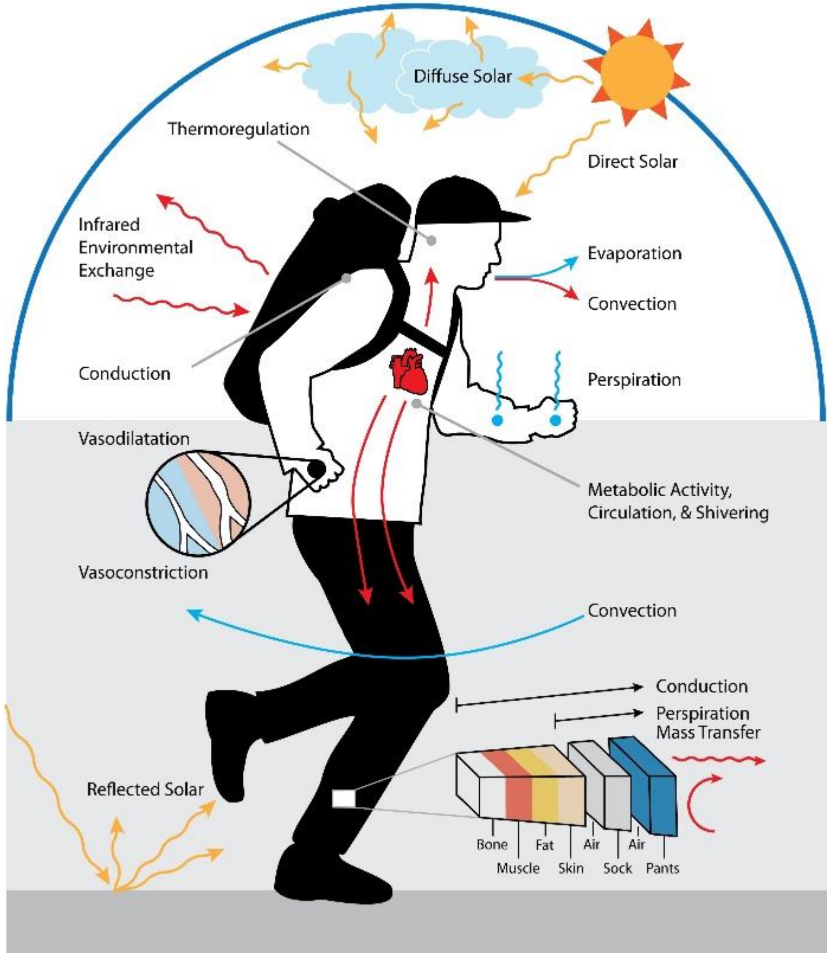
Predicted Mean Vote for HVAC Control

- 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

[6]

TAITherm Human Thermal Model

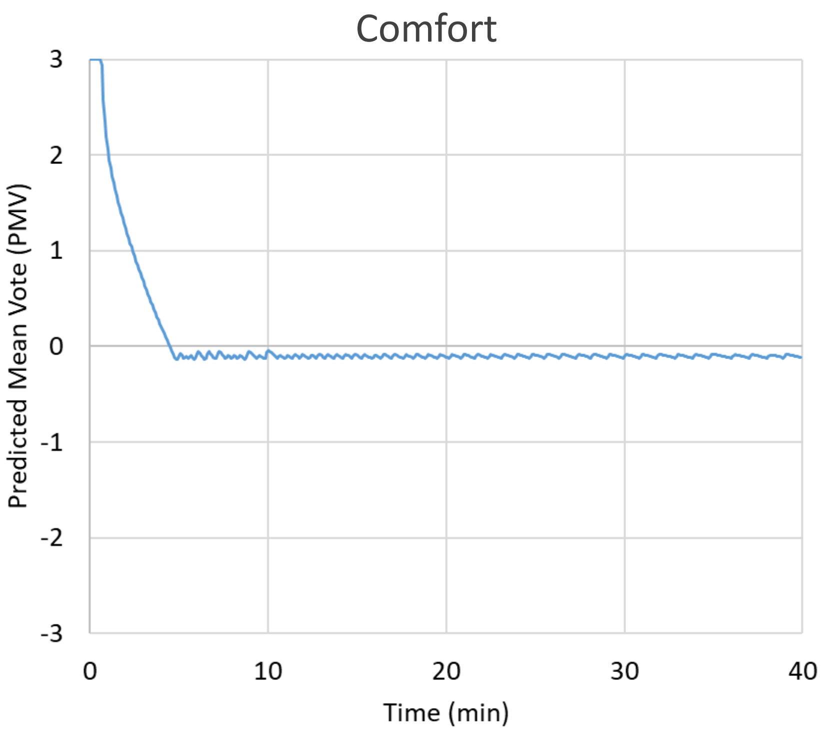
- 20 body segments, with layers representing tissues
- Solves bio-heat transfer equation
- Predicts tissue, blood, and core temperatures under:
  - Varying environmental conditions
  - Varying activity levels
  - Adjustable clothing levels

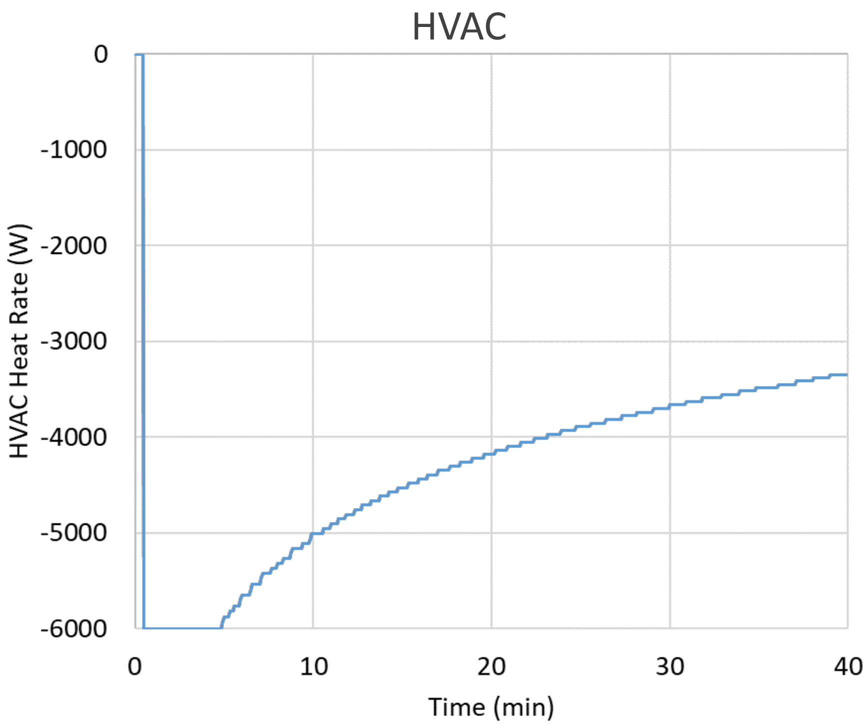


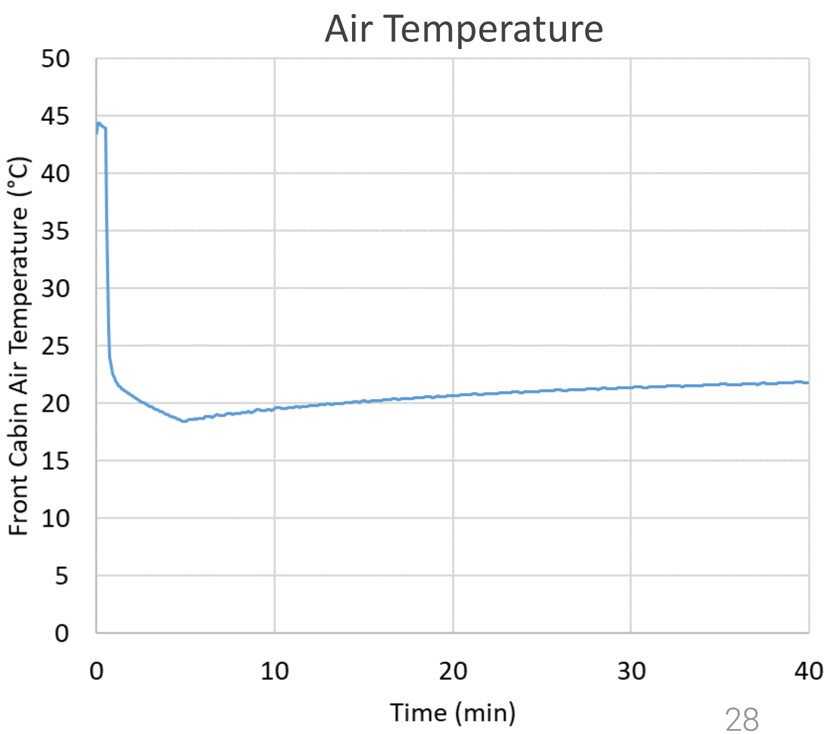
Mechanisms considered by TAITherm Human Thermal Model

Human Comfort for HVAC Power Consumption

- HVAC control algorithm implemented in a User Routine
- $Q_{HVAC} = f(PMV,\ d(PMV)/dt),\ v_{air} = f(PMV,\ d(PMV)/dt)$



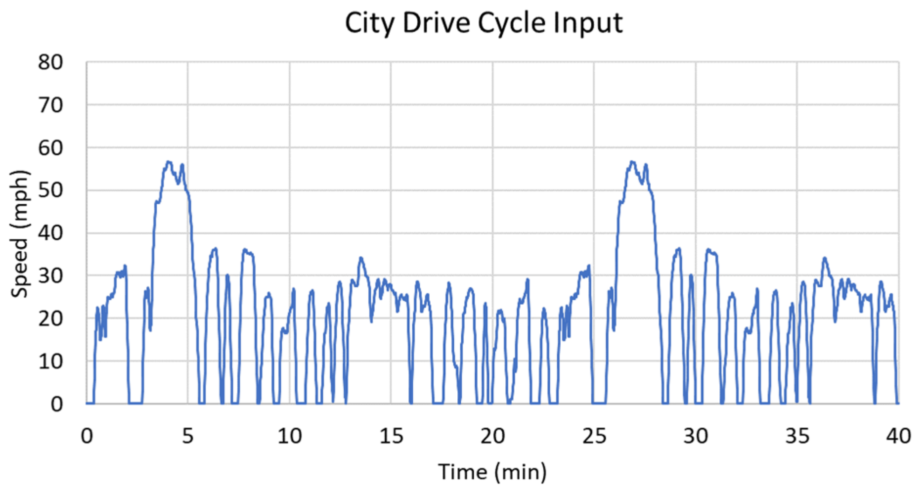


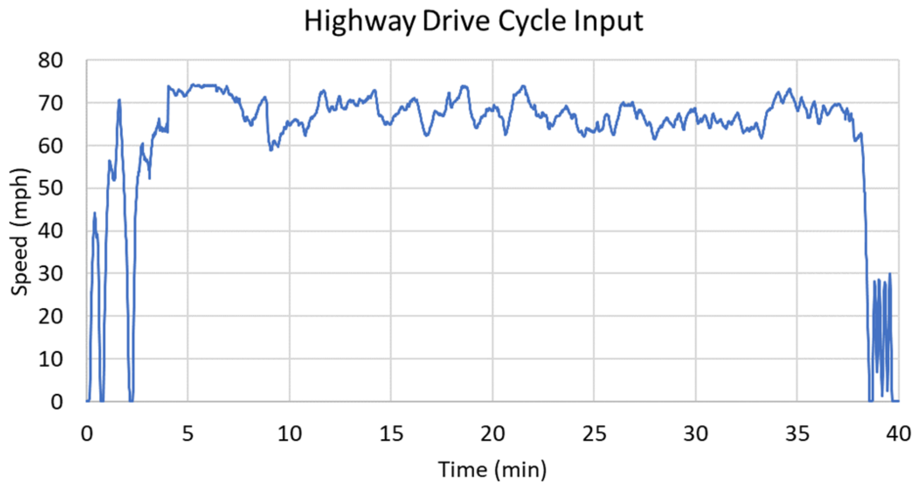


EV Power Model Inputs

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

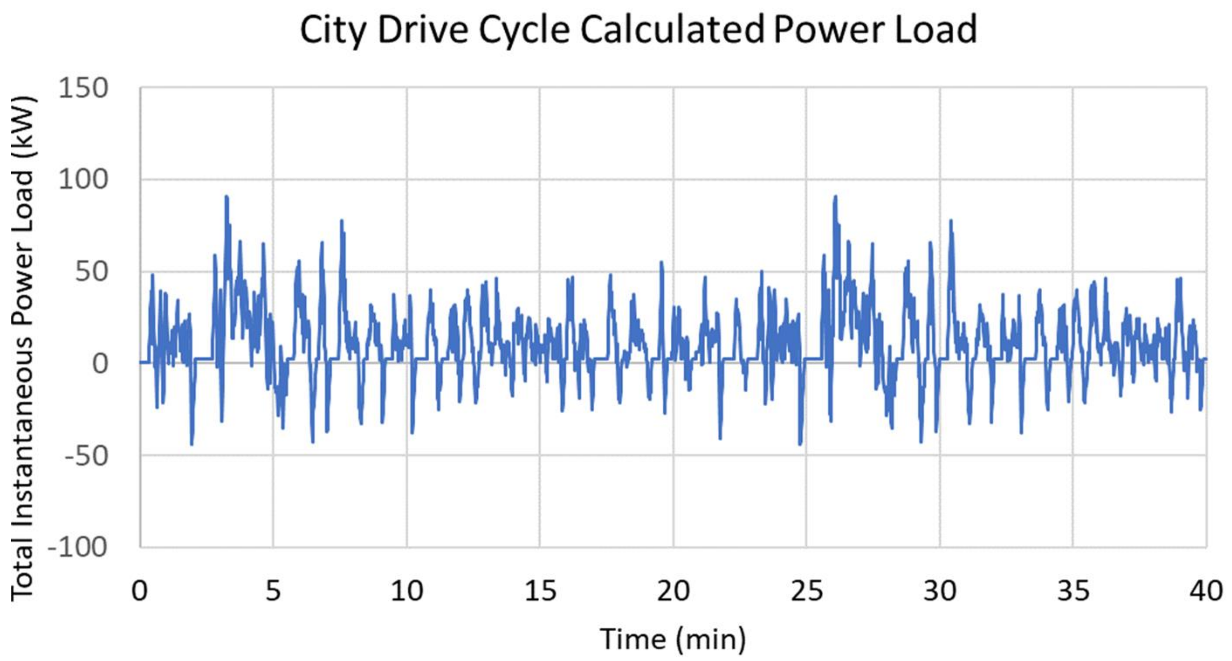
Parameter	Value
Curb Weight	3000 kg
Gear Ratio	8.0
Frontal Area	2.88 m^2
Drag Coefficient	0.371
Max Power	220 kW (300 hp)
Battery Discharging Efficiency	95%
Battery Charging Efficiency	90%
Transmission Efficiency	95%
HVAC Coefficient of Performance	2
Auxiliary Power	0.3 kW

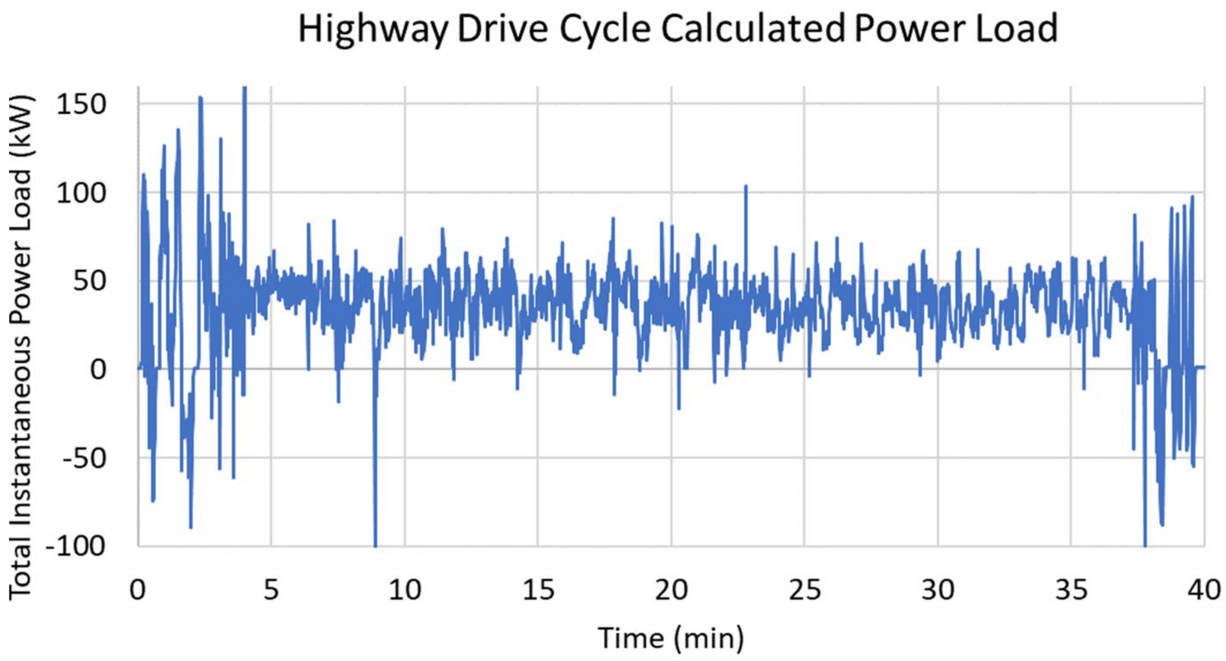




EV Power Model Outputs

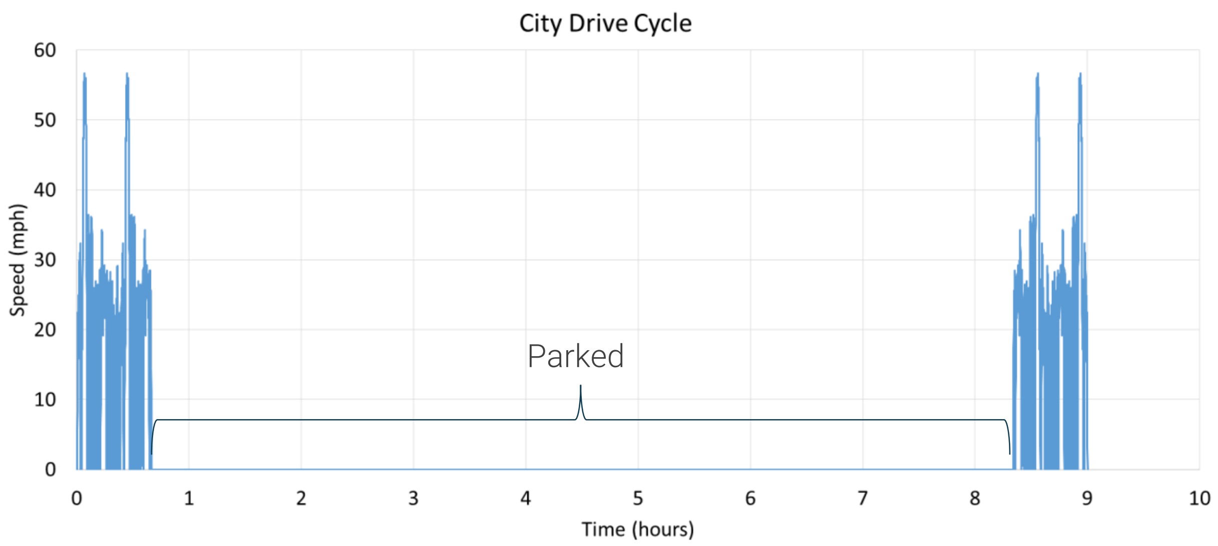
- Total power load time-series
- Power loads and losses from individual components of EV

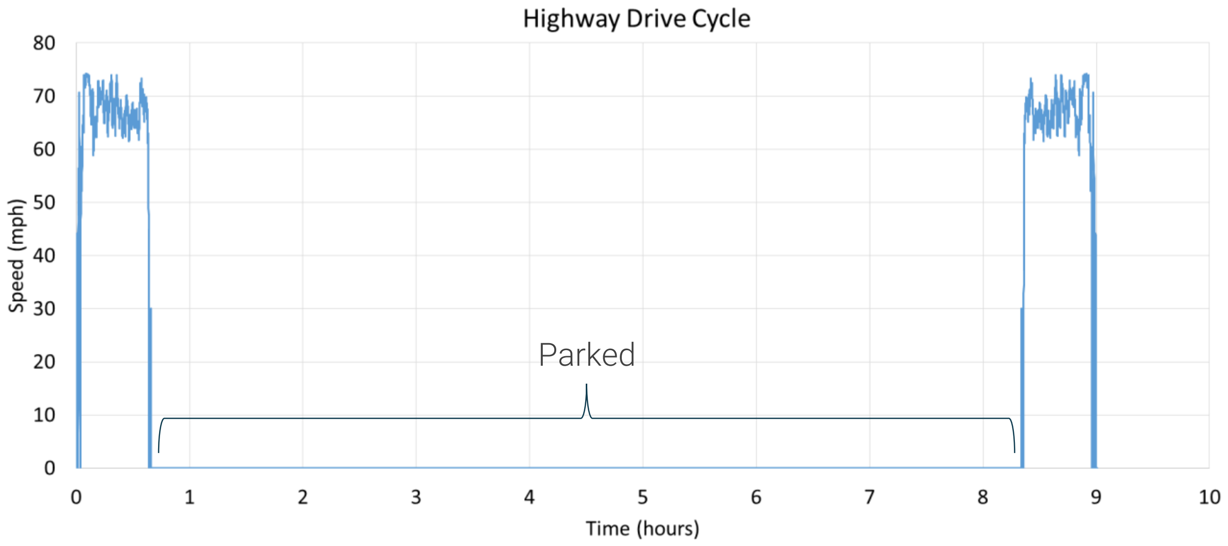




Case Study

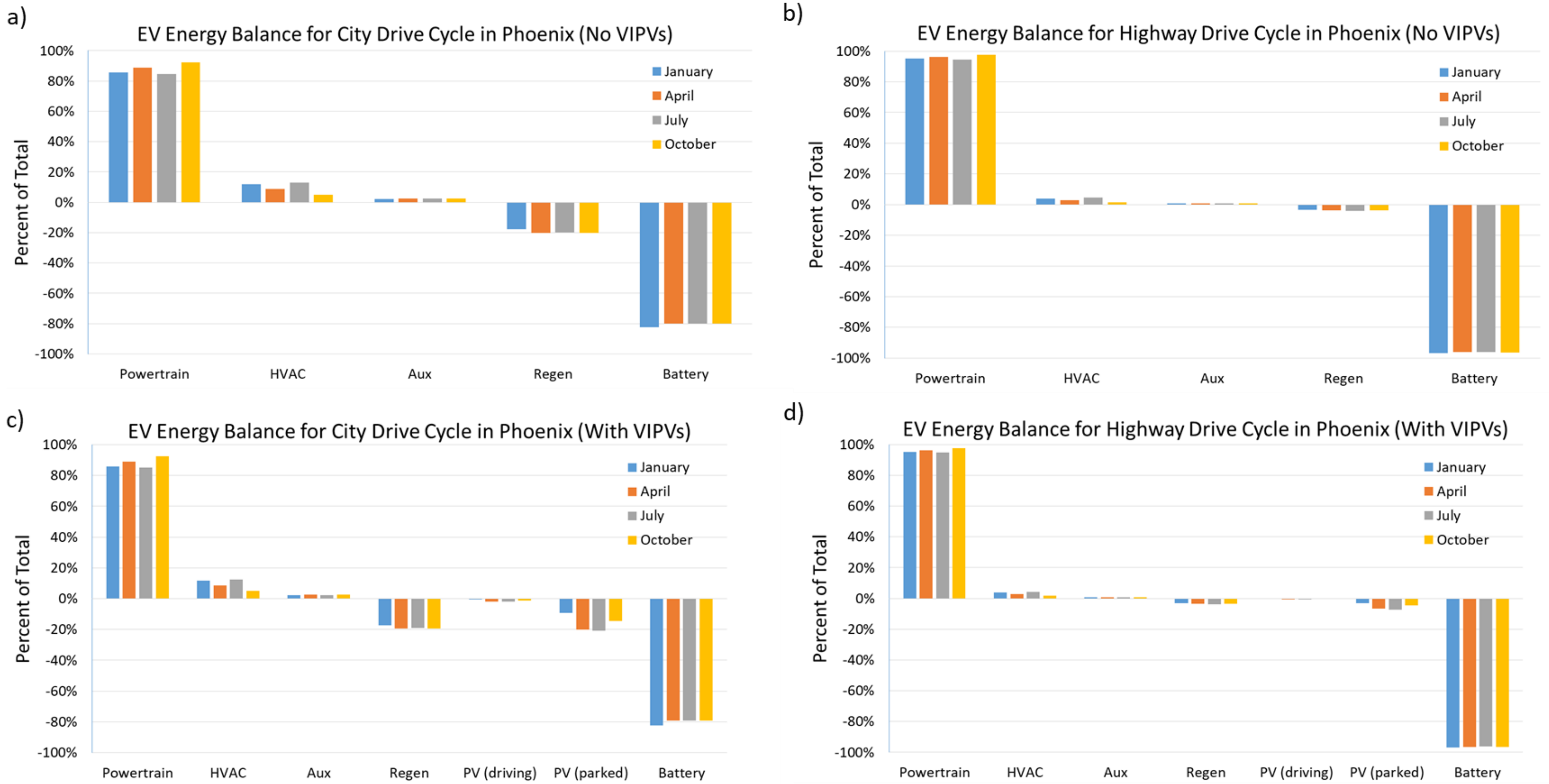
- Modeled EV energy balance over 1 day for 2 drive cycles in each of 4 seasons in Phoenix, Arizona and Detroit, Michigan
  - 40 min morning commute + 8 hours parked outside + 40 min afternoon commute





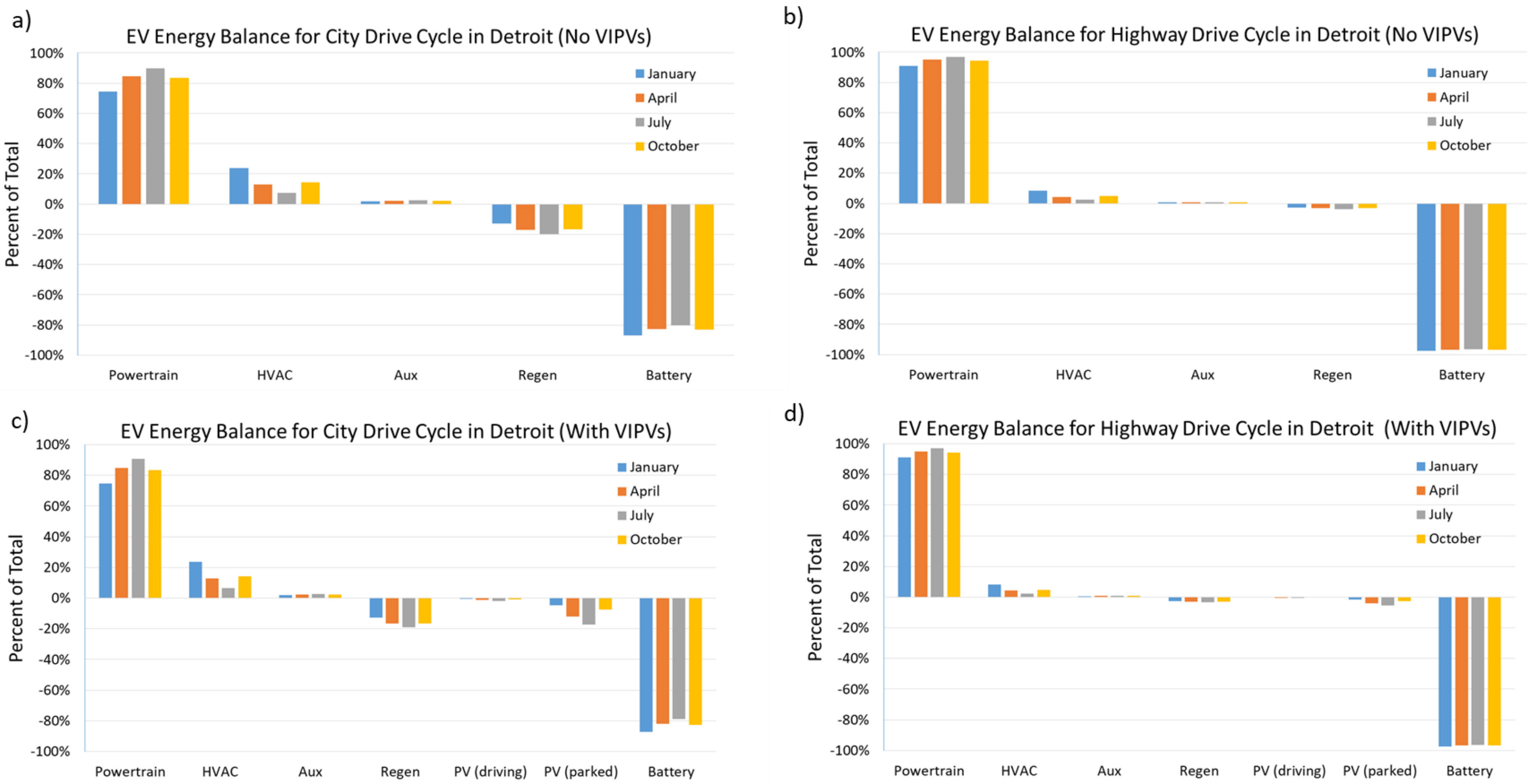
Results: Phoenix, Arizona

- VIPVs generate 10-23% and 3-8% of consumption (or 4-11 km of range) of city and highway drive cycles, respectively



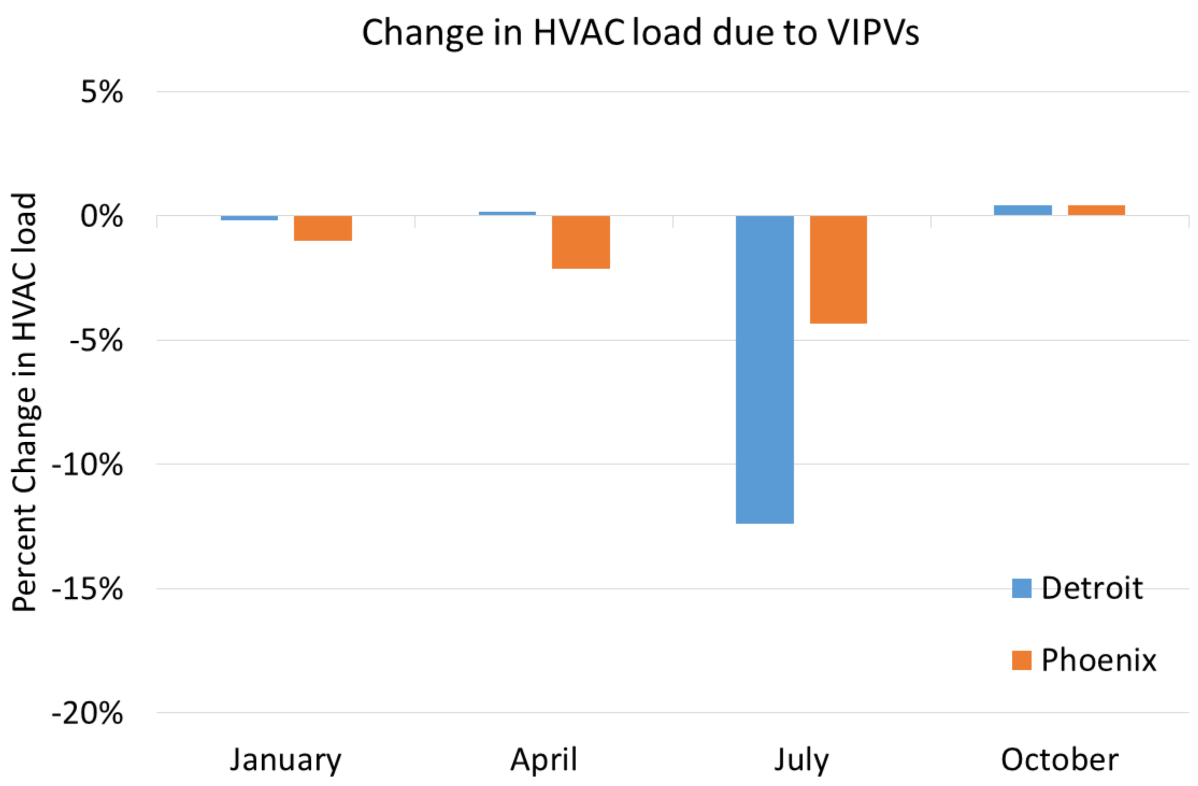
Results: Detroit, Michigan

- VIPVs generate 5-19% and 2-7% of consumption (or 2-9 km of range) of city and highway drive cycles, respectively



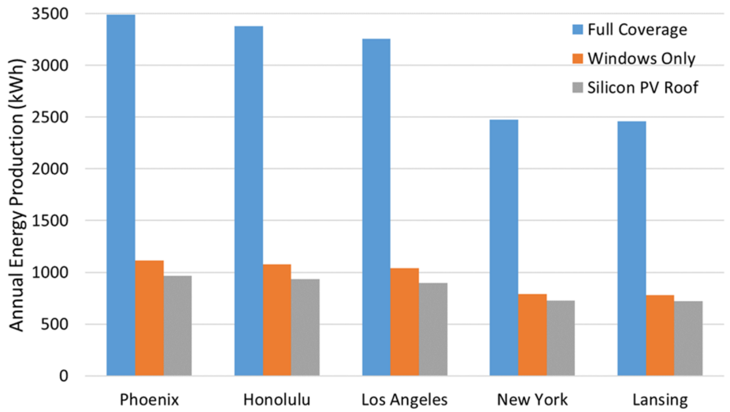
Results: Impact on HVAC Load

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



Conclusions

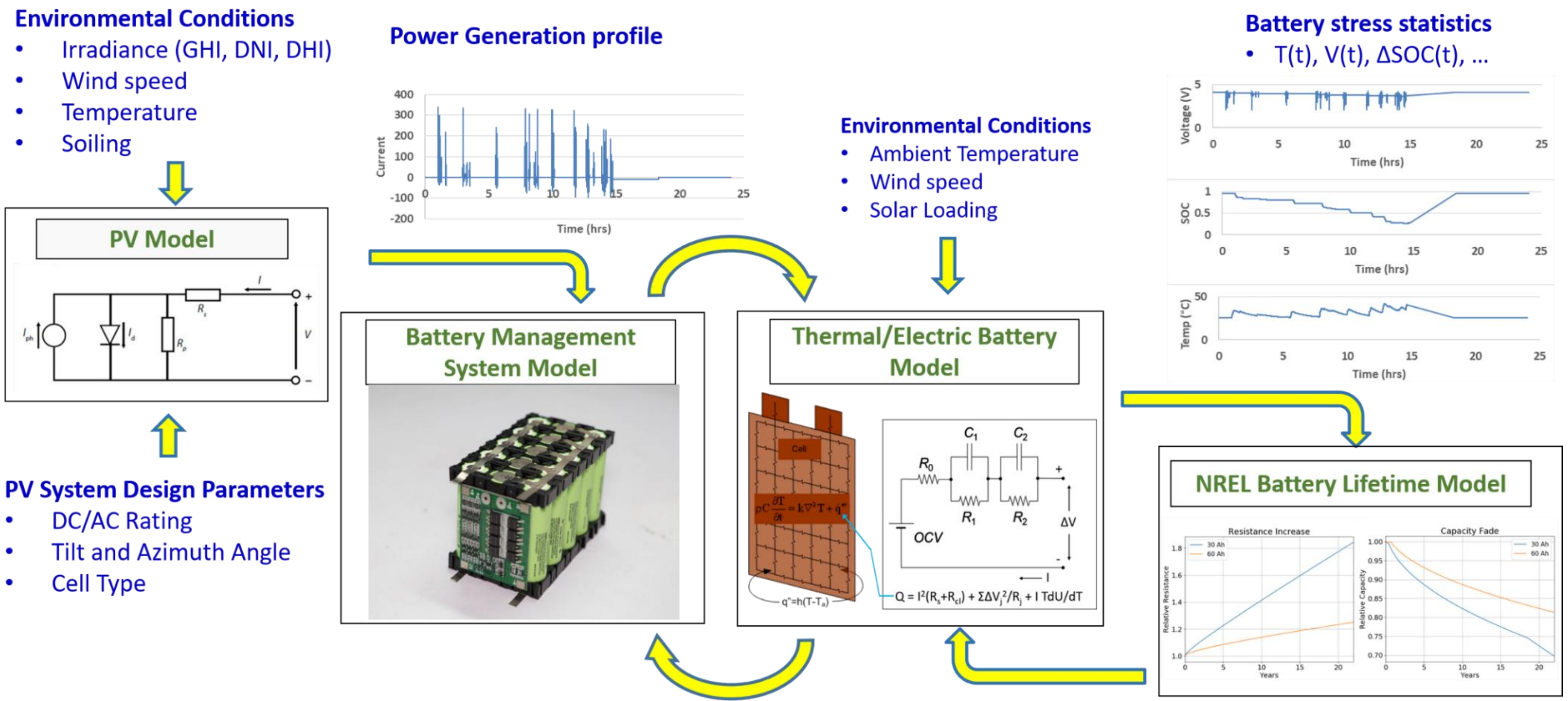
- We demonstrated how TAITherm could be used for EV energy consumption with consideration of VIPVs and HVAC loads
- For a full size SUV, with non-optimized aerodynamics (0.371 drag coeff.), amount of range extension expected from integration of conventional solar cells into the roof and hood is 2-11 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



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4. T. Golubev and R. R. Lunt, "Evaluating the Electricity Production of Electric Vehicle-Integrated Photovoltaics via a Coupled Modeling Approach", 2021 IEEE 48th Photovoltaic Specialists Conference
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6. P. O. Fanger, "Thermal Comfort", Danish Technical Press, Copenhagen, 1970.

Thank you

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