OPV greenhouse solar model & plant response

1. Background (theory, physics, biology)  
   1. Agrivoltaics 🡪 OPV greenhouse
      1. Agrivoltaics definition  
         1. Agrivoltaics is an increasingly popular concept in food-energy nexus realm, describing the integration of renewable energy technologies into agricultural systems. Agrivoltaics manifests itself in many different forms, including the application of photovoltaics (PV) to greenhouse production systems. Especially in the context of global population increase and climate change, protected crop production, with its relatively high space efficiencies and climate independence, is increasingly seen as a critical component of our food system. However, greenhouses are relatively energy-intensive compared to conventional field agriculture. With the goal of making greenhouse systems more viable food production systems economically and environmentally, many have considered the integration of PV panels with a greenhouse structure, enabling the production of food and electricity on the same land area. A greenhouse that could supply its own energy demand solely from its own structural materials is an exciting thought.
         2. One promising option for greenhouse-integrated PV is in thin-film, semi-transparent PV (TFST-PV) materials, which can share incident solar radiation between PV cells and crops growing underneath them. This project is looking at a particular type of thin-film, semi-transparent PV – organic PV (OPV), whose photoactive layer is mostly comprised of semi-conductive organic polymers. OPVs have many advantages over other types of TFST-PV, including fine-tuneability of spectral characteristics, environmental sustainability (i.e. source materials and recyclability), and low manufacturing costs. OPVs can also be directly printed onto glass and plastic substrates, making them structurally compatible with greenhouse covering materials.
         3. However, several factors must be considered when integrating any TFST-PV, including OPV, onto a greenhouse roof. First, OPVs have relatively low power conversion efficiencies (PCE) compared to conventional rigid, opaque PV (5% commercial PCE for OPV compared to 20% commercial PCE for conventional PV). How much power is the integrated OPV actually producing, and is it worth the trouble (i.e. cost of OPV materials, installation, eventual replacement)? Second, how is the semi-transparent OPV material affecting sunlight qualities and quantities entering the greenhouse? How much and what kind of light is being transmitted and absorbed by the photosynthetic organisms inside the greenhouse, and how does this affect their growth and development?
         4. In order to test these questions, eight OPV rolls, each roll consisting of eight OPV modules, each module consisting of four OPV cells wired in series, were installed on the roof of a gothic-arch, polyethylene-clad greenhouse at the University of Arizona Controlled Environment Agriculture Center (UA CEAC). For initial power output monitoring, the OPV rolls were centered on the apex of the greenhouse roof, one half of the roll facing east and the other half facing west. Over the course of several months (November 2019 to February 2020), current voltage curves were measured for each OPV roll from 6AM to 6PM, one roll monitored each day. Next, and currently underway, is a plant response experiment for the OPV greenhouse. The OPV rolls will be relocated to cover the northern half of the greenhouse grow area, leaving the southern half exposed. Tomato and lettuce crops will be grown inside of the greenhouse, with the two treatments being under OPV and not. Light measurements will be taken inside the greenhouse
      2. Integrating photovoltaics onto greenhouse roof
         1. Advantages
         2. Things to consider
            1. OPV efficiency
            2. Plant response
   2. Solar radiation on inclined surface
      1. Greenhouse roof and integrated OPV geometry
         1. Solar incidence angles of OPV for given date and time
      2. Direct beam radiation
      3. Diffuse radiation
      4. Global radiation
      5. OPV PCE
   3. Shading of OPV rolls on greenhouse grow area
      1. Transmittance through greenhouse covering material
         1. Type of covering material
            1. Double-layer polyethylene
      2. Light qualities
         1. Spectroradiometer measurements
   4. Greenhouse crop response to different lighting treatments/shading
      1. Light for greenhouse crops
         1. PPFD
         2. DLI
      2. Tomato
         1. State variables of interest
      3. Lettuce
         1. State variables of interest
2. Flowchart  
   1. Solar model (radiation incident on greenhouse for any date and time) 🡪 shading model (greenhouse grow area shaded) 🡪 growth models for tomato and lettuce (yield in shaded vs. unshaded) 🡪 overall system efficiency with solar inputs (efficiency of plants / efficiency of OPV)
3. Plan