End-to-end design of PV systems including variability and reliability

NEEDS 2012-2017 (needs.nanohub.org)
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What were the goals?

The goal of the project was to develop an atoms-to-farms end-to-end modeling framework for solar cells, the first of this kind for the industry. The modeling framework addresses length scales over 15 orders of magnitude (from nm to km) and time scales of 16-17 orders of magnitude (ns to years). The end-to-end perspective allows one to assess the relative importance of device-level solar cell parameters for the ultimate cost of energy harvested from a solar farm. The framework will address questions of device and module design with an intimate understanding of quality and reliability of the solar cells. And, ultimately the system perspective would allow one to develop inverse modeling approaches where the instantaneous data from the solar farms can be used to assess the health of a given installation (inverse modeling).

What was accomplished?

While the development of the models were supported from a variety of sources, NEEDS provided the critical resources to develop the compact models and make the software platform accessible to the community.

Under this modeling program, the following tools were developed:

a) Thermodynamic Limits. A calculator for thermodynamics limits for single and tandem solar cells called **PVLimits** was developed and installed [1]. The calculator and the related papers answer fundamental questions related to the efficiency of the solar cells and for the first time demonstrates the efficiency limits of bifacial tandem solar cells [2, 3].

b) Light Absorption in Solar Cells. Optical modeling of light absorption in variety of solar cell technologies, including Si, GaAs, CIGS, OPV, and perovskite [4, 5]. The importance of wavelength-specific light trapping, the relevance of photonic structures to reduce entropy production, the importance of photon-recycling, the trade-off between light-absorption and carrier transport, were considered in detail.

c) Carrier Transport. Detailed modeling of carrier transport in solar cells, including the validity of superposition in silicon and heterojunction solar cells, were analyzed in detail. The importance of interface recombination, especially for HIT, OPV, and perovskite cells have been established [6,7]. An undated version of the device simulation, **ADEPT-2.1**, has been deployed [8–10].

d) Importance of Parasitic Shunt Formation. The group defined the universality of shunt formation across multiple technologies and explained why the shunt conduction is described by a lon-normal distribution [11,12]. A simulator called **PVAnalyzer** takes experimental data as input and extracts corresponding device parameters as output [13].

e) Compact Models. Based on the physics-based models above, the Alam group has developed compact models for almost all commercially relevant cell technologies, including Si, HIT, CIGS, CZTS, OPV, perovskite [14–17]. And the model predictions have been verified against broad range of collaborations with various experimental groups from Purdue, NREL, IIT-Bombay, Berkeley, EPFL, Moser-Baer, Selivo, AMAT, Kaust, and so on. The compact models for the solar cells (called **PSM**) has been posted in the NEEDS website [18].

f) Compact Models and Tandem Cells. Based on the compact model developed above, the group has explored the importance of two junction tandem cells. The optimization of bifacial HIT-perovskite tandem cells has been of broad interest to the community [19].

g) Characterization Methodologies. The group has analyzed in detail a broad range of characterization techniques, such as C-f, C-V, Suns-Voc, reverse-leakage [20]. They have demonstrated that none of the techniques in isolation allows unique extraction of the device parameters. Only a collection of techniques, within the framework of a multiprobe, characterization "triangulates" the parameters for predictive modeling. **ADEPT-2.1** embeds a simulation option (called Frozen potential approach) to test superposition in solar cells [10].

h) Module Performance. The group has integrated the cell level information for both monolithic thin-film solar cells as well as discrete c-Si solar cells using a simulator called **PVPanelSim2.0** [21]**.** The implications of cell level variability on module efficiency in determining the cell-to-module efficiency gap have been established [22].

i) Reliability of Modules. Hot spot formation and shadow-induced degradation are one of the most important reliability mechanisms for solar cells. A careful and detailed analysis, in collaboration with NREL, has formed the basis of the revised qualification standard for the industry [23]. Purdue's contribution to the topic is widely recognized. **PVPanelSim2.0** will contain these updates. Models for other degradation mechanisms, such as PID and corrosion, are being developed [24]. Techniques to improve reliability though self-cooling of the solar cells are also being developed [25].

j) From Modules to Solar Farms. Atlases of solar energy production for variety of farm topologies have been developed. This will be the first report regarding the vertical bifacial farms and the relative advantage with respect to the monofacial farm. The careful study will be a significant contributor to the understanding of farm design for the new generation of cell technologies. A simulator that can help farm design is being developed and will be posted.

k) Storage of Solar Energy. Solar cells produce energy during the day. The energy must be stored for night-time use. A variety of technologies (e.g. pumped hydro, redox battery, etc.) have been proposed, but the fundamental limits of energy storage are not fully understood. The group has developed a model that calculates the fundamental limits of energy storage for a given combination of solar cells and storage mechanism. The approach also illustrates how the cells must be optimized for maximum energy storage. PVLimits2.0 will feature these updates.

In addition to the research contributions through publications and modeling tools, the group has posted at YouTube several educational resources featuring lectures regarding all aspects of solar cells. These lectures have been viewed hundreds of thousands of times by viewers all across the world. The work has been featured in Nature, Science, PNAS, IEEEE Journal of

Photovoltaics, IEEE Trans. On Electronic Devices, Applied Physics Letters, Nanophotonics, Optics Express, Journal of Physical Chemistry, Energy and Environmental Sciences, Progress in Photovoltaics, etc. The articles have been downloaded several thousand times.

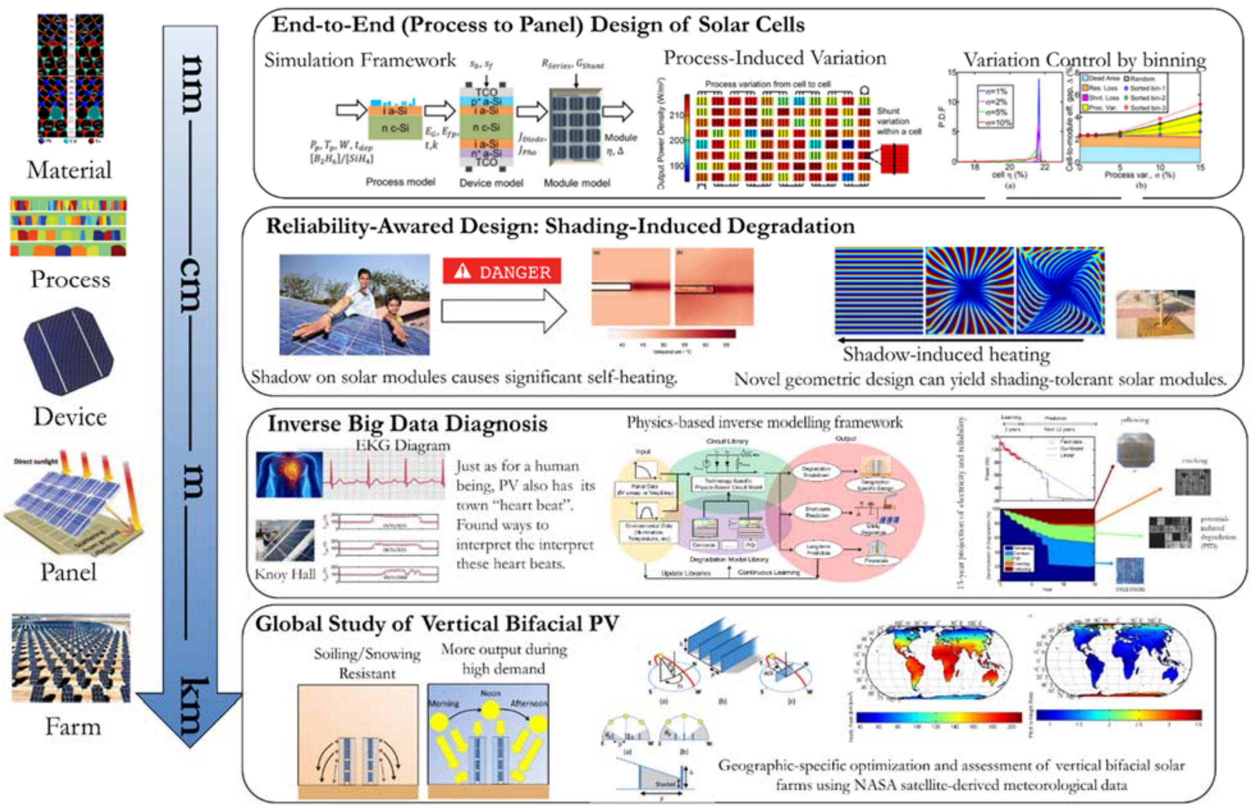

Figure 1. Illustration of the "atoms to farms" photovoltaic modeling system.

Why was it important?

The work has been very important because this is for the first time one can discuss and optimize process, device, module, or farm topology within a comprehensive self-consistent framework. The relationship among the variables are now transparent, allowing one to focus on elements of device physics that would produce the most impact (system-aware device innovation). The modeling framework also allowed a redefinition of industrial qualification standard for shadow degradation – the first such redefinition based on the results of modeling. Finally, the work has been instrumental in defining the performance limits of bifacial solar cell and perovskite solar cell technologies, two of the most important emerging field of research/commercialization in the field. Finally, the online simulation and educational tools (nanohub.org/groups/pv) will be a community resource of great value.

The development of the toolset has allowed the Alam group to emerge as a key enabling partner for NREL, Sandia National Lab, Seriius program, and BAPVC consortium. Multiple students have done their Ph.D. on the topic, and they have all benefitted from the vision associated with the project that only an end-to-end modeling framework can ensure self-consistent analysis of various changes on the cell technologies.

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