Optics of Solar Cells

Greg P. Smestad, Ph.D.
Solar Energy Materials and Solar Cells, USA
and Sol Ideas Technology Development

OSA's 93rd Annual Meeting - San José, CA, USA,
Frontiers in Optics (FiO) 2009/Laser Science (LS)
25th Conference

Optics for Renewable Energy

Keynote Speaker: FMB1, Optics of Solar Cells, Greg P. Smestad, Monday, October 12, from 1:30 PM - 2:15 PM

- Systems Approach
- Optical view of Solar Cells and Photovoltaics
- Literature
- What else is it good for?
- Solar Energy Grid Interconnection Systems (SEGIS)
- Solar R&D Plan
- Where we go from here?

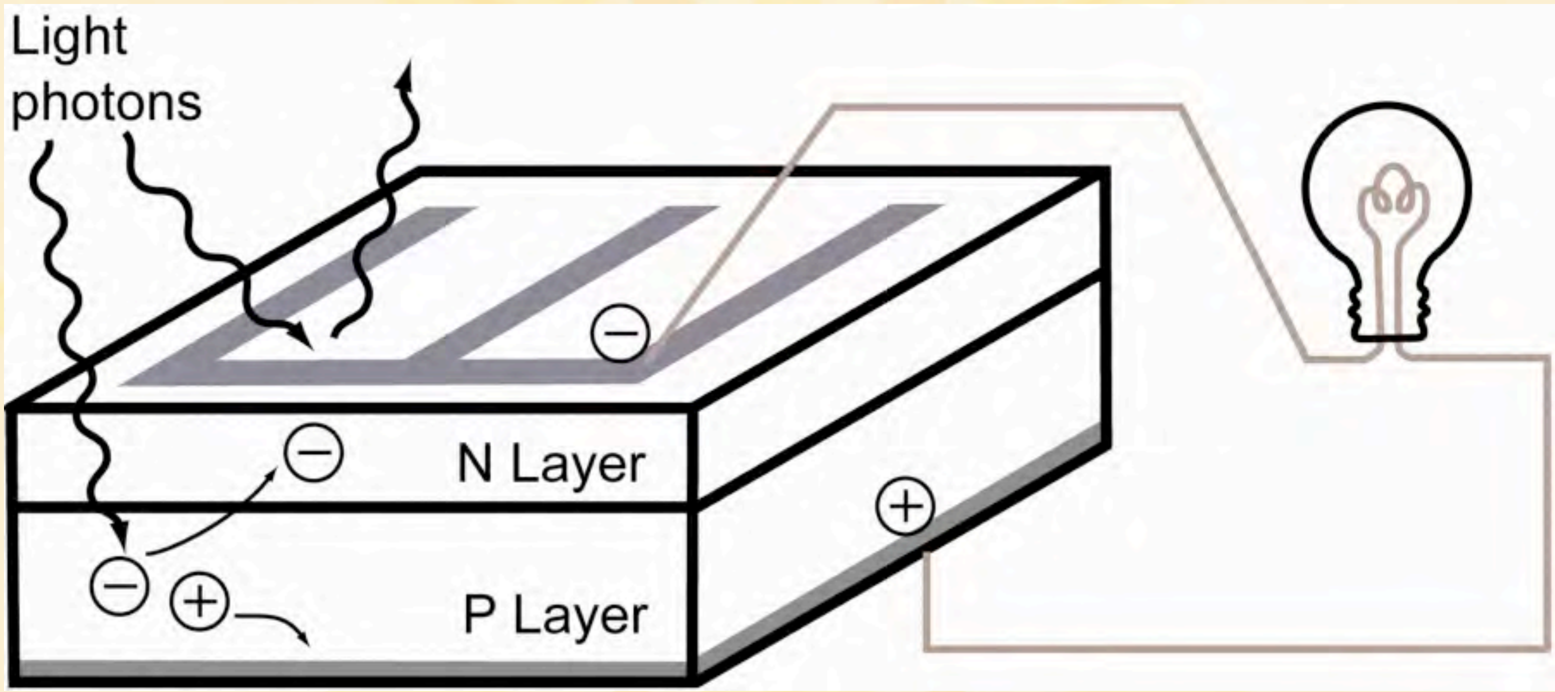
What are Systems?

- A system is a group of interacting, interrelated, and interdependent components that form a complex and unified whole.
- Systems are everywhere:
  - ✓ the R&D department in your organization,
  - ✓ the circulatory system in your body,
  - ✓ a photovoltaic cell or **PV system.**

Systems Thinking is

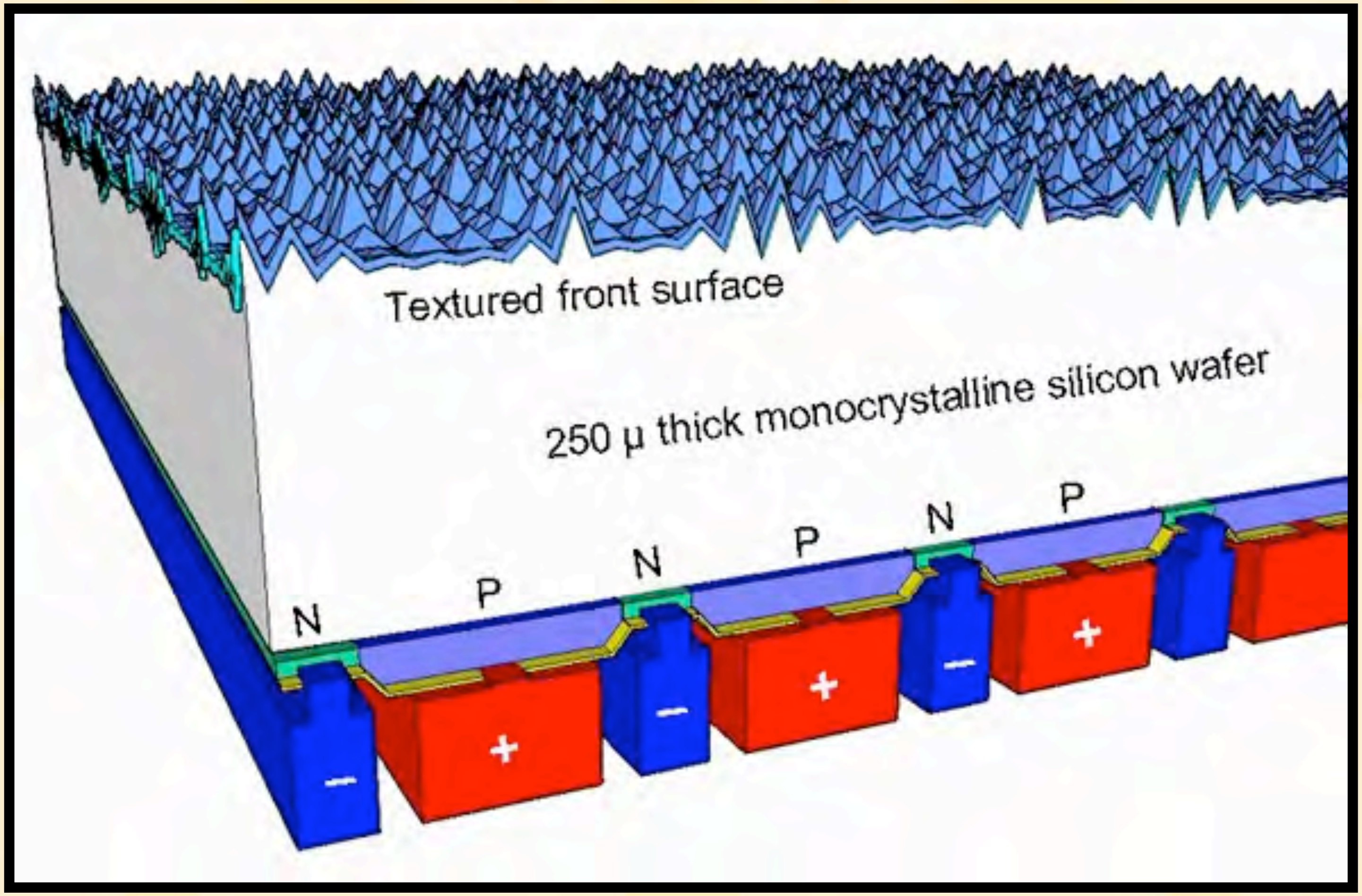
- a framework that is based on the belief that the component parts of a system can best be understood in the context of relationships between components and with other systems, rather than in isolation.
- It seeks an understanding of a system by examining the linkages and interactions between the elements that comprise the whole system.
- **Let's look at a solar cell as a thermo-dynamic system**

Solar Cells can be simple, but



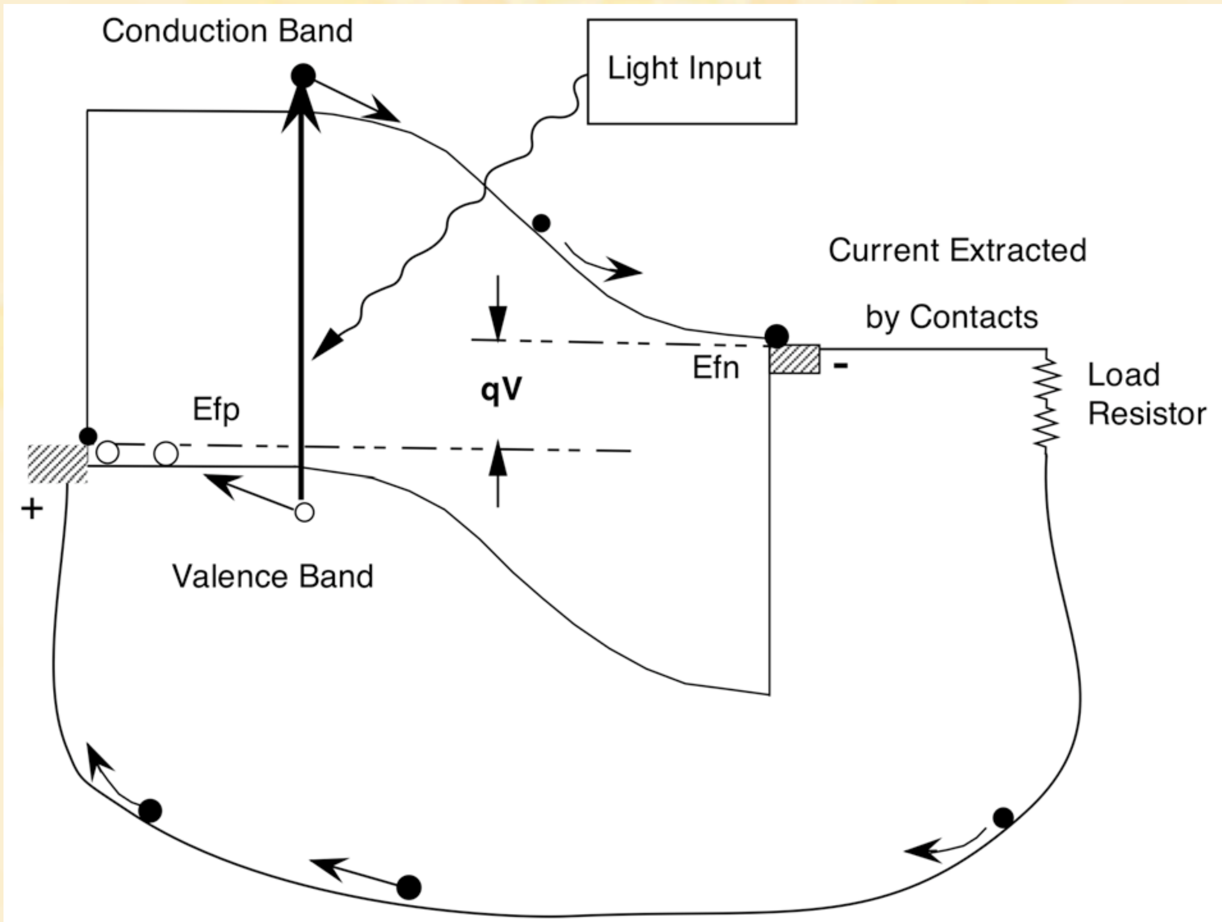
Courtesy: G.P. Smestad

they can also be complex.



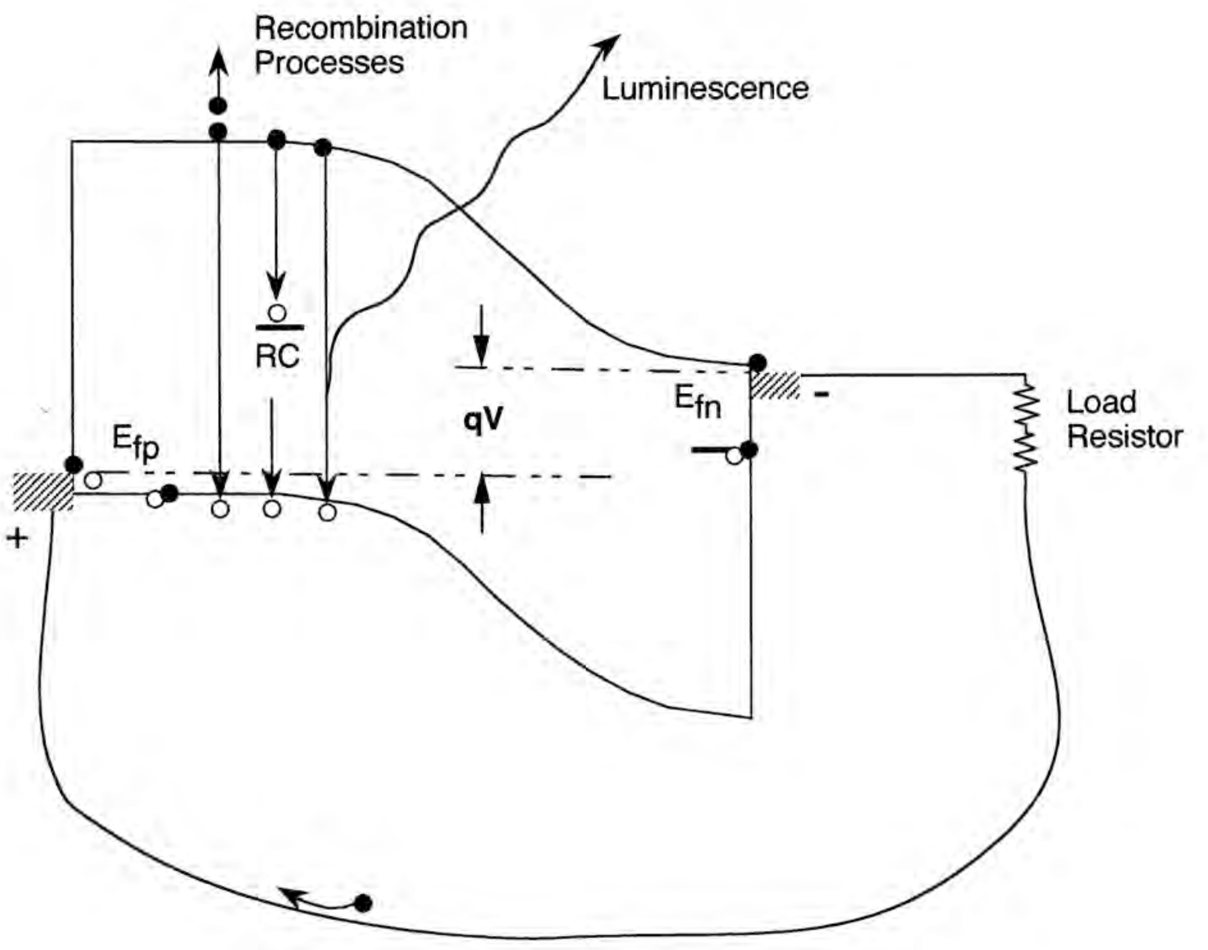
Courtesy of Dick Swanson, *SunPower*

Band Diagrams are useful, but



Courtesy: G.P. Smestad

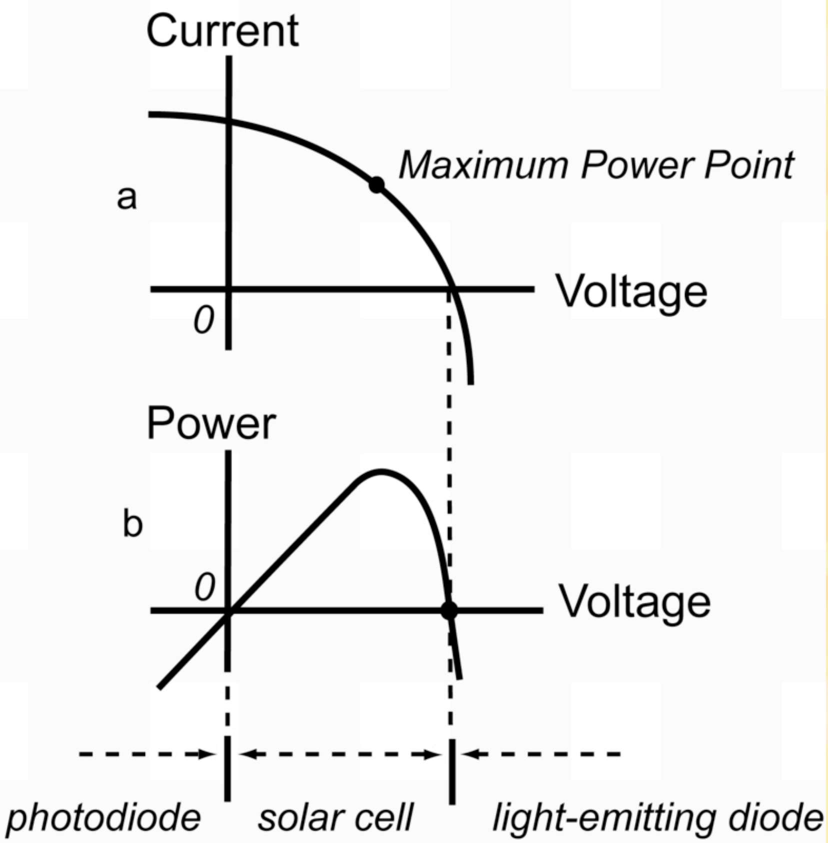
recombination determines efficiency.



Courtesy: G.P. Smestad

Diode Equation

$$I(V) = I_{SC} - I_0\left[\exp\left(\frac{qV}{\gamma kT}\right) - 1\right]$$



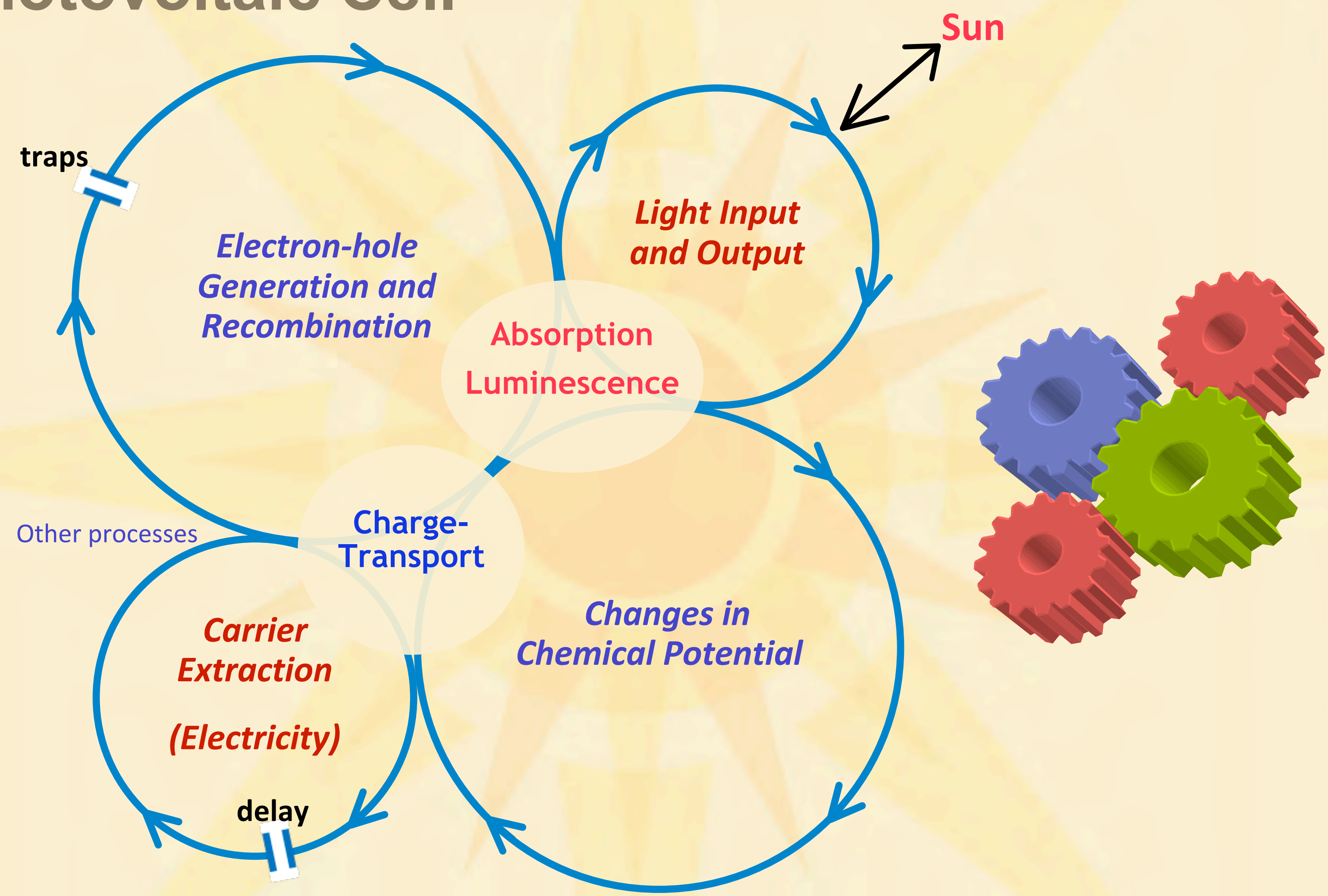
Device Electrical Characteristics

Courtesy: Alexis de Vos

System Properties

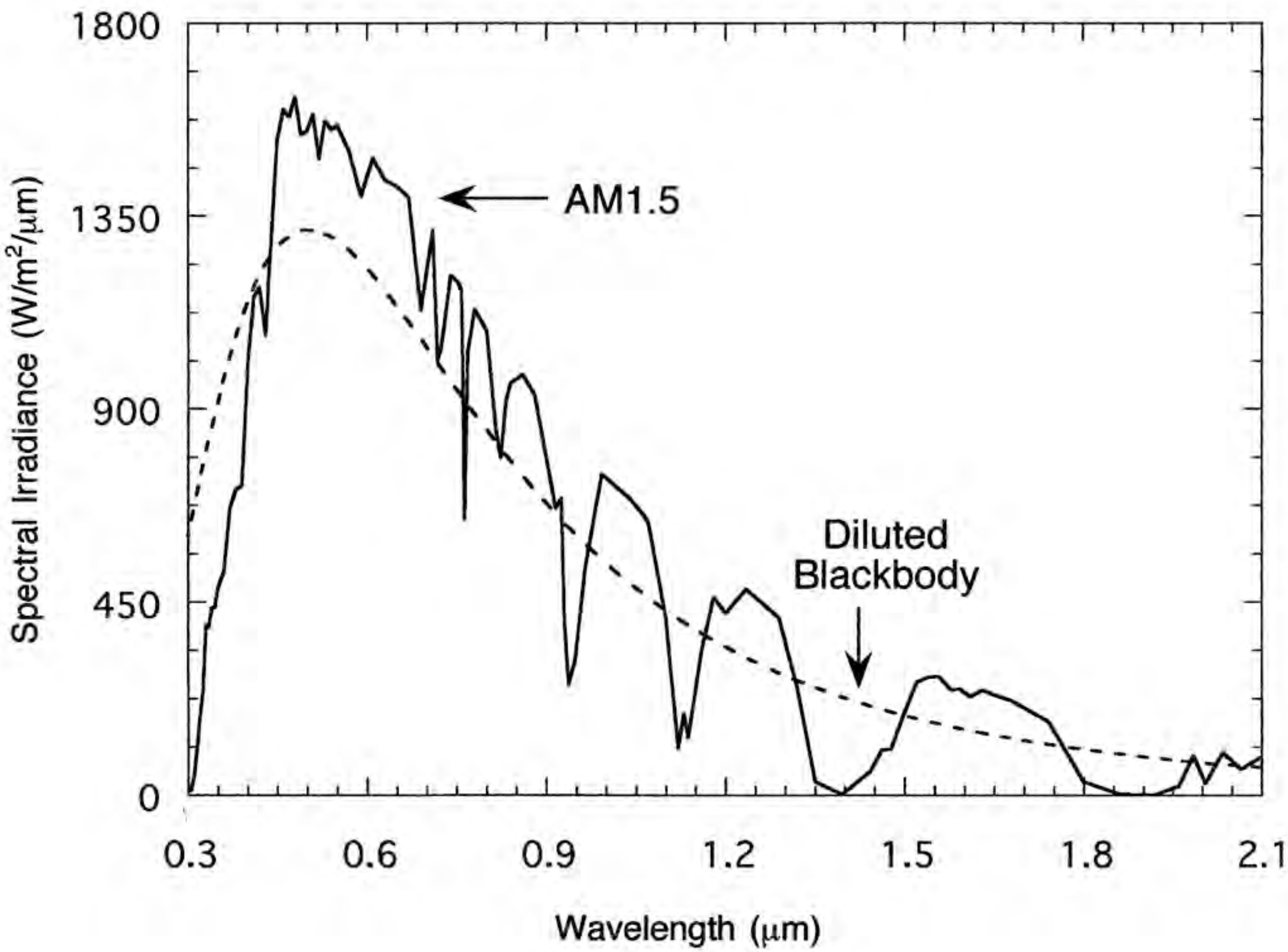
- Energy, material and information are among the different elements that comprise the system and these flow
  - to and from the surrounding environment via semi-permeable membranes, **barriers** or boundaries.
- Systems are often composed of entities seeking equilibrium and can exhibit exponential behavior.
- Entropy - the amount of disorder or randomness present in any system.

Senge Diagram
Photovoltaic Cell



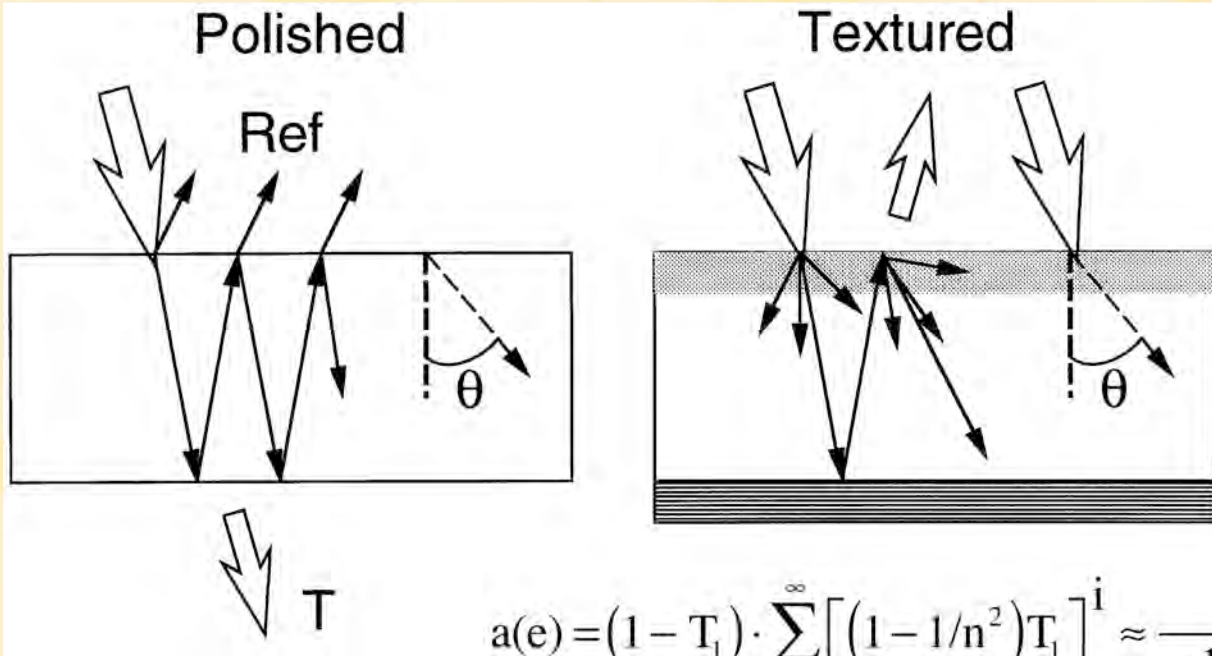
Courtesy: G.P. Smestad

The Planck Equation describes solar radiation, but



Courtesy: G.P. Smestad

absorptivity describes what is absorbed.



$$a(e) = (1 - T_1) \cdot \sum_{i=0}^{\infty} \left[\left(1 - 1/n^2\right) T_1 \right]^i \approx \frac{\alpha}{\frac{1}{4tn^2} + \alpha\left(1 - \frac{1}{n^2}\right)}$$

E. Sacks/MIT/1366 Technologies;
Veeco Instrument Inc. Optical Profiler

Generalized Planck Equation

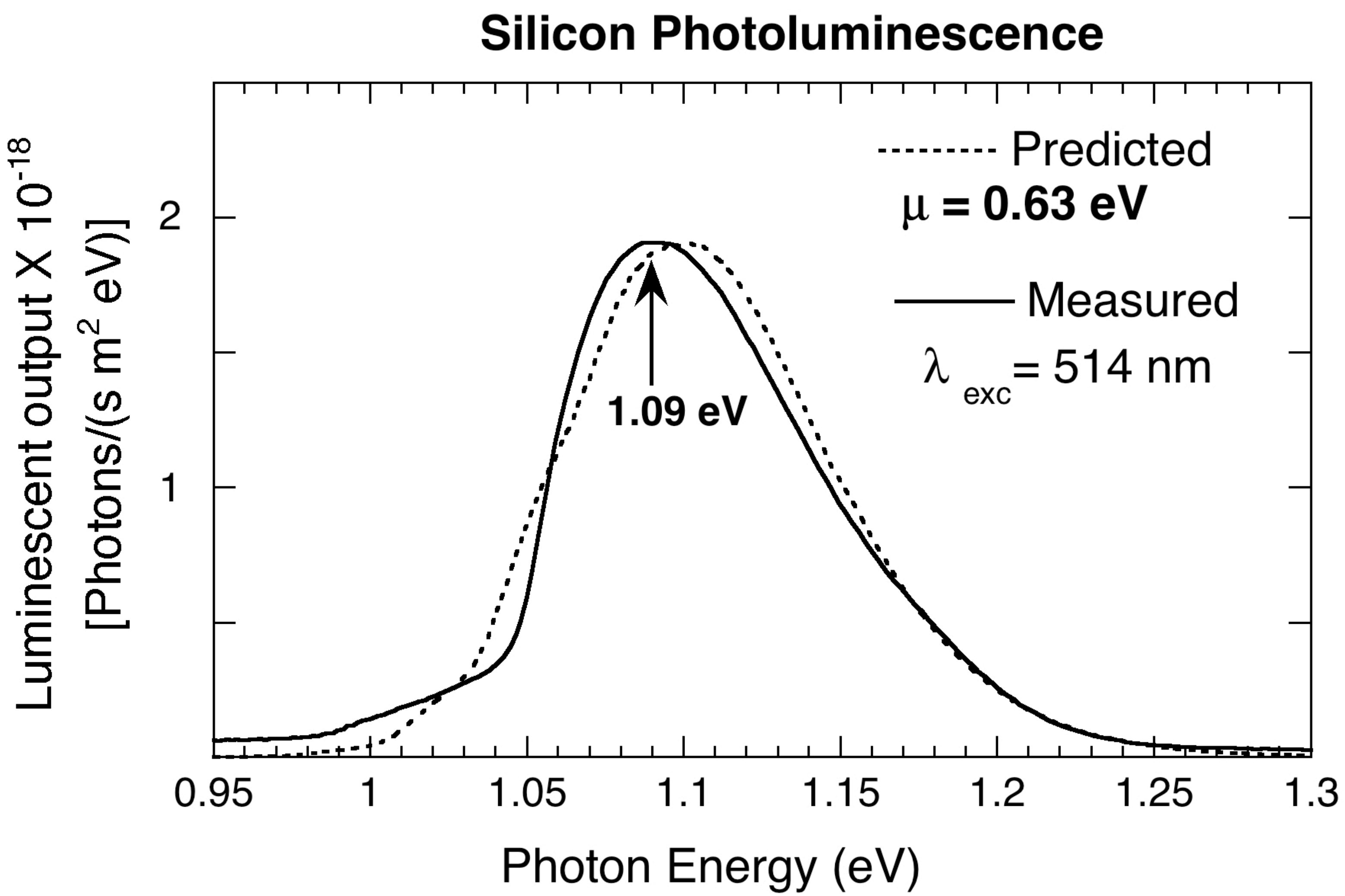
$$\mu = e\left(1 - \frac{T_0}{T_S}\right)$$

$$\frac{(e - \mu)}{kT_0} = \frac{e}{kT_S}$$

Sun

$$L_x(e, \mu, T_0) = \varepsilon(e) \frac{2\,n^2}{h^3\,c^2} \frac{e^3}{\exp\frac{(e - \mu_x)}{kT_0} - 1}$$

Planck Describes Rad. Recombination



Courtesy: G.P. Smestad

Define and Integrate

$$L_x^{'}(e,\mu,T_0)=\frac{L_x(e,\mu,T_0)}{e\cdot\varepsilon(e)}$$ Ideal Spectral Flux

$$a(e)=\varepsilon(e)$$ *Quantum* Kirchhoff's law

$$\Gamma_0=\int_0^\infty \varepsilon(e)\,\pi\,L_0^{'}\,de$$ Photons *(Particles)*

Detailed Balance

$$\Phi_{OC}(\mu, T_0) \equiv \Phi = \frac{\text{Radiative Recombination}}{\text{Total Recombination}}$$

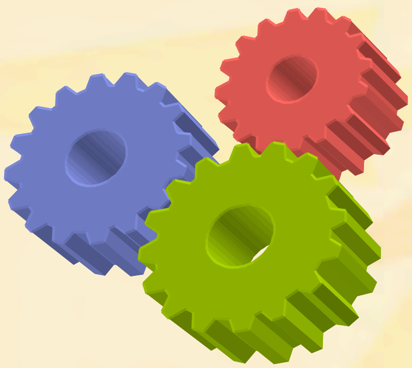
Ambient Incident + Solar Incident =

Luminescent Photons + Phonons or Heat + Current extracted

$$\Phi = \frac{\Gamma_{0R} - \Gamma_0}{\Gamma_S} \cong \frac{\Gamma_0 \exp(\mu/kT_0) - \Gamma_0}{\Gamma_S}$$

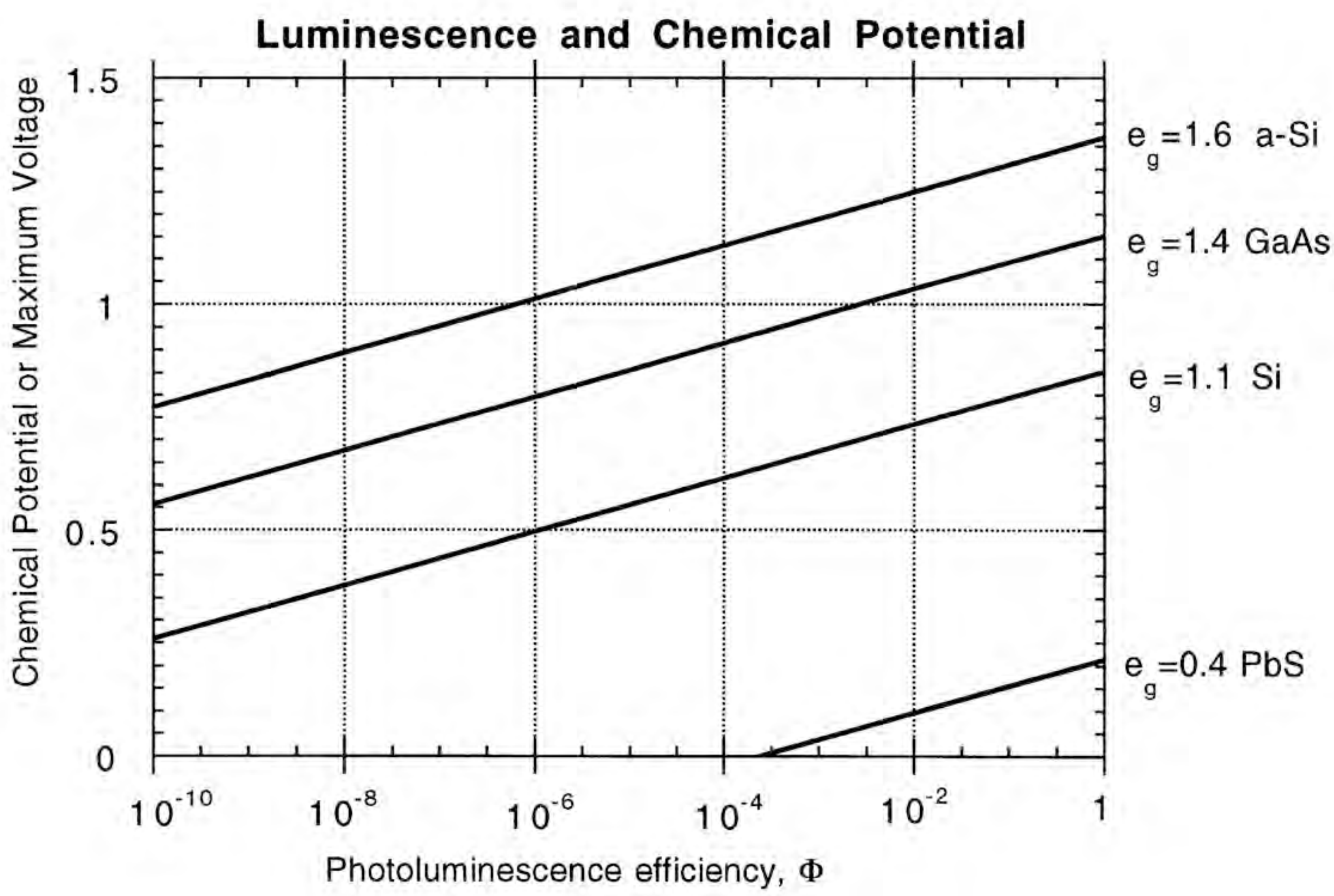
Diode Equation emerges from Planck

$$\Gamma = \Gamma_S - \frac{\Gamma_0}{\Phi}\left(\exp\frac{\mu}{kT_0} - 1 \right)$$



$$\text{max. chemical potential} \equiv \mu_{max} \approx kT_0 \ln\frac{\Gamma_S}{\Gamma_0} + kT_0 \ln\Phi$$

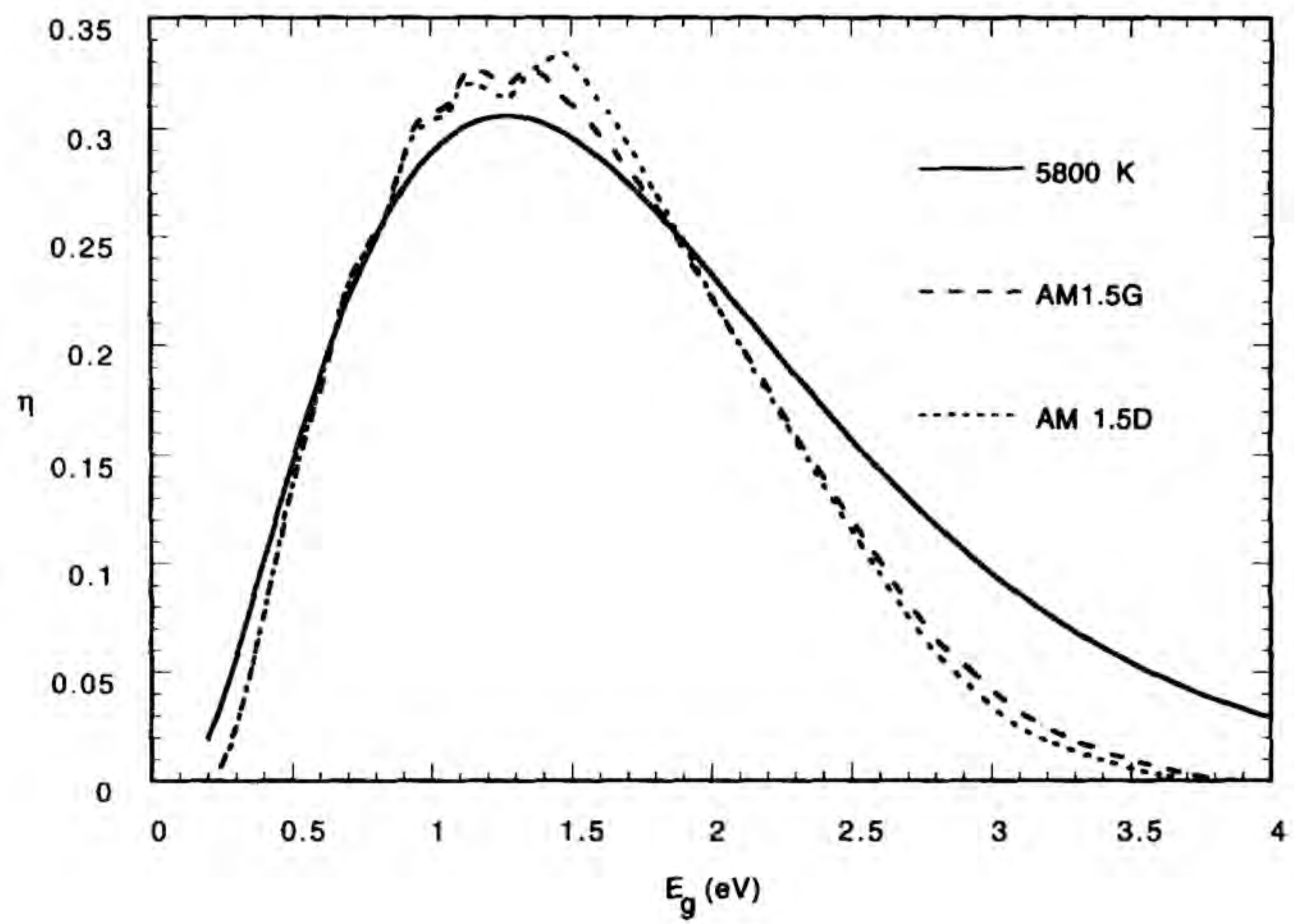
Radiative Recombination



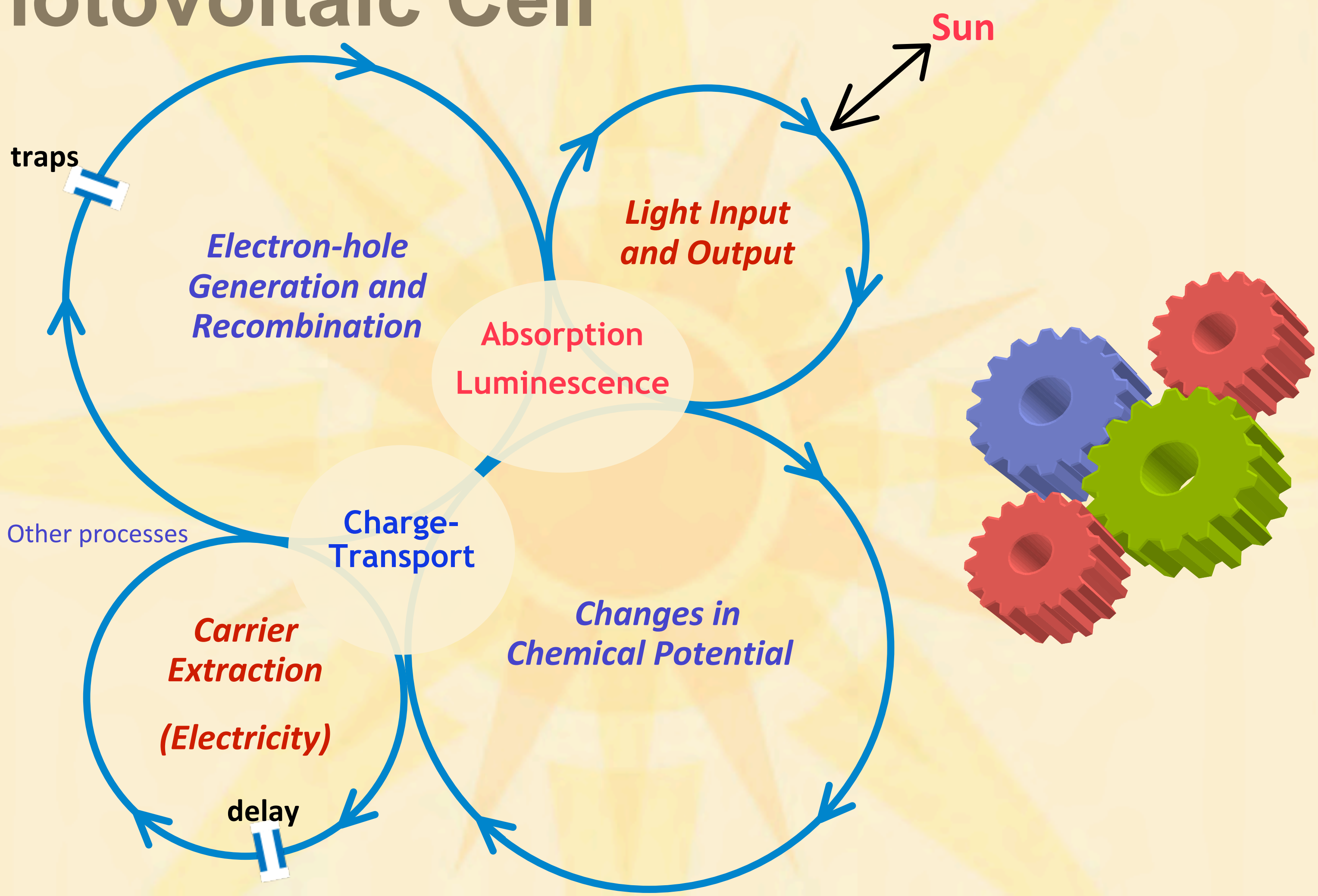
Courtesy: G.P. Smestad

Detailed Balance Efficiencies

P. Baruch et al. / Solar Energy Materials and Solar Cells 36 (1995) 201–222



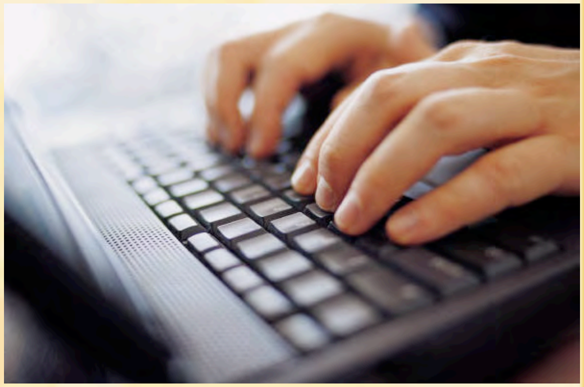
All from a Systems Approach to a Photovoltaic Cell



A Solar Cell is a System

- The performance of solar cells is determined by how its materials absorb, reflect and even emit light.
- The voltage produced can be described using the Planck equation rather than the Fermi-Dirac equation.
  - In other words, solar conversion can be viewed from the standpoint of the **photon** rather than the **electron**.
- Such an optical *Systems Approach* can be useful for understanding solar cell-device designs and the fundamental limitations to conversion efficiency for a given absorption.

Want More on this Optical Perspective?



- Look for publications by:
  - ✓ Shockley and Queisser
  - ✓ Harald Ries
  - ✓ P. Wuerfel (Würfel)
  - ✓ E. Yablonovitch and G. Cody
  - ✓ R. T. Ross
  - ✓ T. Markvart
  - ✓ T. Trupke
  - ✓ PV Optics Computer Program: B. Sopori

  www.nrel.gov/pv/measurements/computational_modeling.html

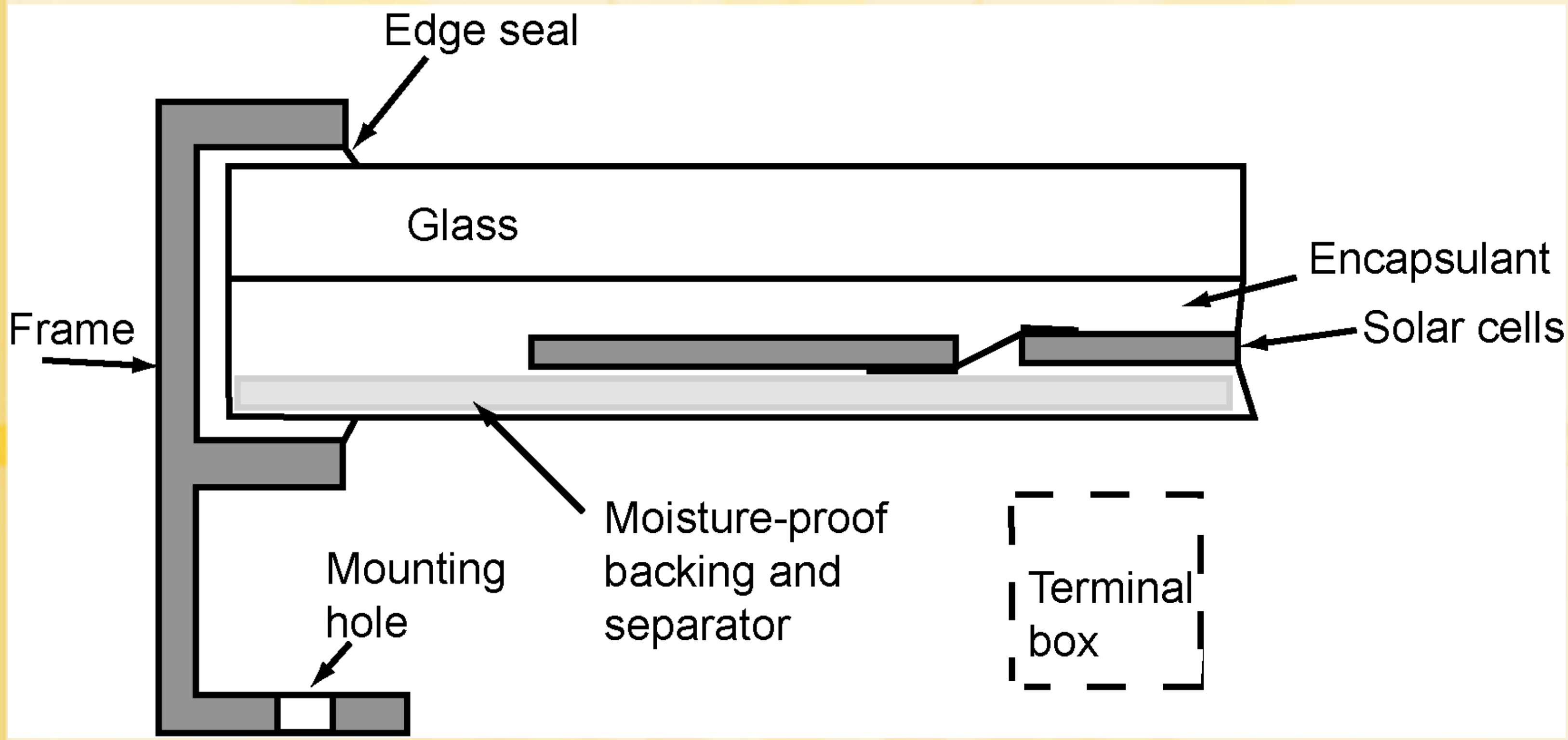
and (yes) Greg P. Smestad

- G. Smestad, "Absorptivity as a predictor of the photoluminescence spectra of silicon solar cells and photosynthesis," Solar Energy Materials and Solar Cells, 38, 57, 1995.
- Greg P. Smestad, Book: "Optoelectronics of solar cells," SPIE Tutorial Vol. PM115 (International society for optics and photonics); ISBN 0-8194-4440-5,118 pages; Pub. July 2002; Softcover.

What else is it good for?

- Systems thinking techniques may be used to study any kind of system: natural, scientific, engineered, human, or conceptual.
- *Systems Analysis* for solar R&D can identify key positive reinforcements that can accelerate the adoption of solar technologies. It can identify constraints that can decelerate solar technology adoption, as well as points of leverage where investment and R&D can have the most positive impact.

PV Module Systems



K. R. McIntosh, R. M. Swanson and J. E. Cotter, A Simple Ray Tracer to Compute the **Optical Concentration of Photovoltaic Modules**, Prog. Photovolt: Res. Appl. 2006; 14:167-177.

Residential Systems

Smart Grid - **Solar Energy Grid Interconnection Systems (SEGIS)**

http://www.sandia.gov/SAI/

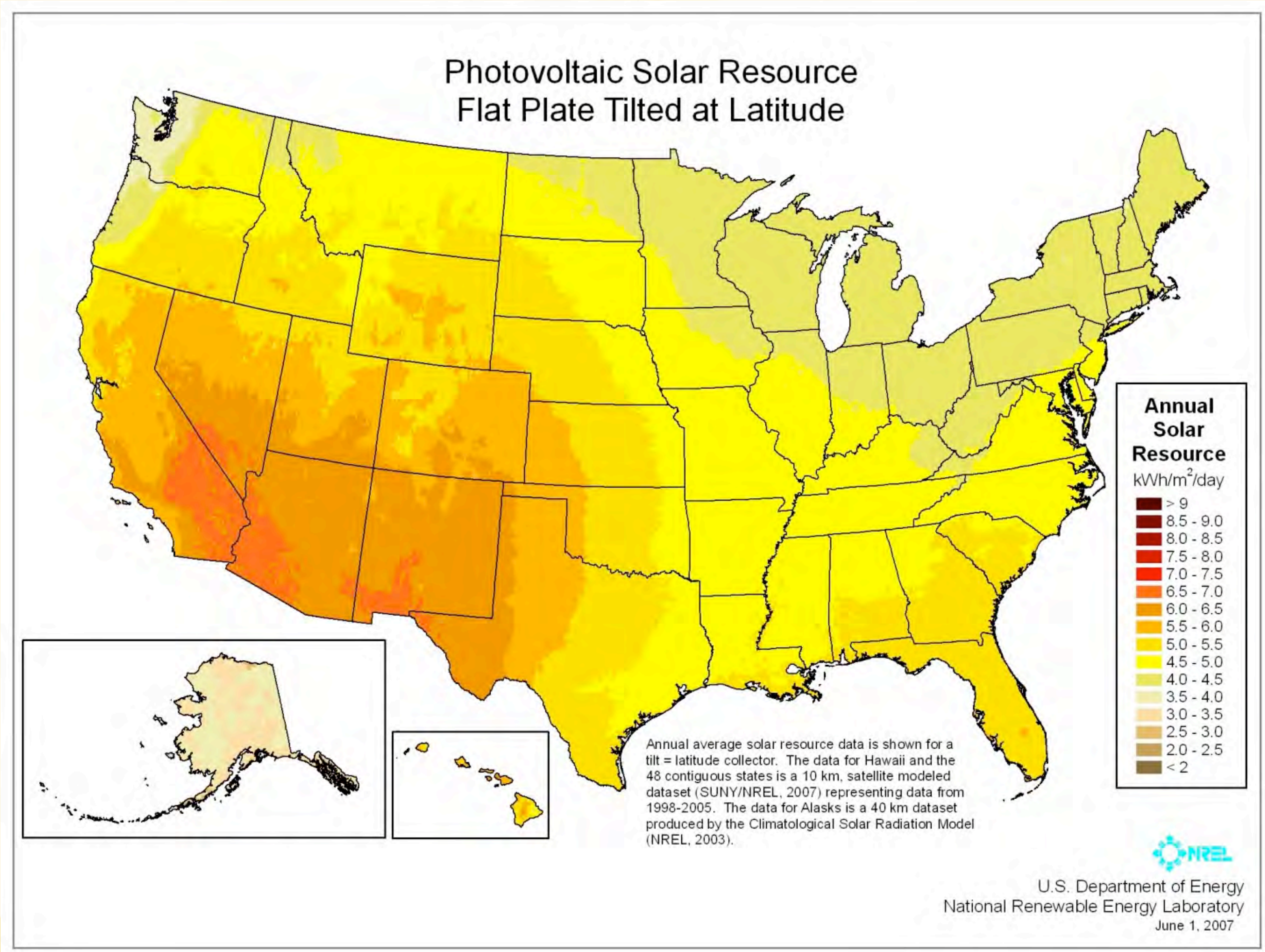
Courtesy: *Ron Smestad*

PV Systems Connected to Grid

Sources: NREL photos/Arizona Public Service facility in Prescott; SolFocus

The Solar Advisor Model (SAM) evaluates several types of financing (from residential to utility-scale) and a variety of technology-specific cost models for several and, eventually, all solar technologies.
https://www.nrel.gov/analysis/sam/

SEGIS Dynamics needs Real-Time Data



Solar Resource Monitoring

Book by Stuart Bowden and Christiana Honsberg; http://pvcdrom.pveducation.org/

Courtesy: NREL Photos

Senge Diagram —

Representation of System-Focused Solar Industry Development

The Solar Industry:

- Similar to automobile industry in ultimate scale—and hence,
- Expect large companies designing complete systems from integrated subsystems delivered by a network of suppliers.
- Can get "there" from "here" via —

The Energy Internet:

- Will evolve from today's grid
- Can use the Information Internet as model for development
- Key elements include: standards, consumers and producers, a network and an infrastructure for transport and storage
- Can start with —

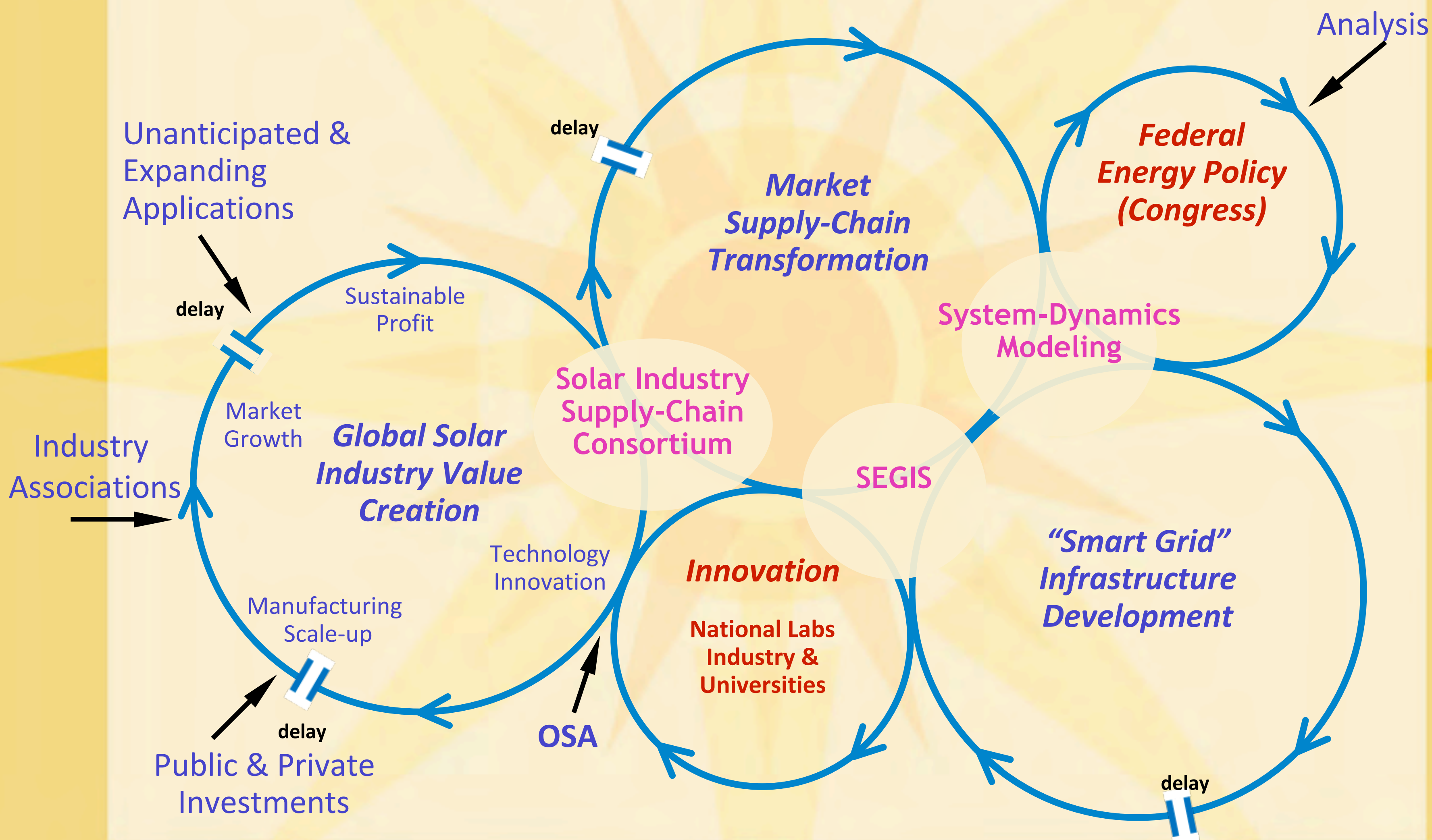
Global Solar Industry Value Creation

How do these relate?

"Smart Grid" Infrastructure Development

Courtesy: Joe Morabito, Alcatel-Lucent, DOE/SETP March 2009

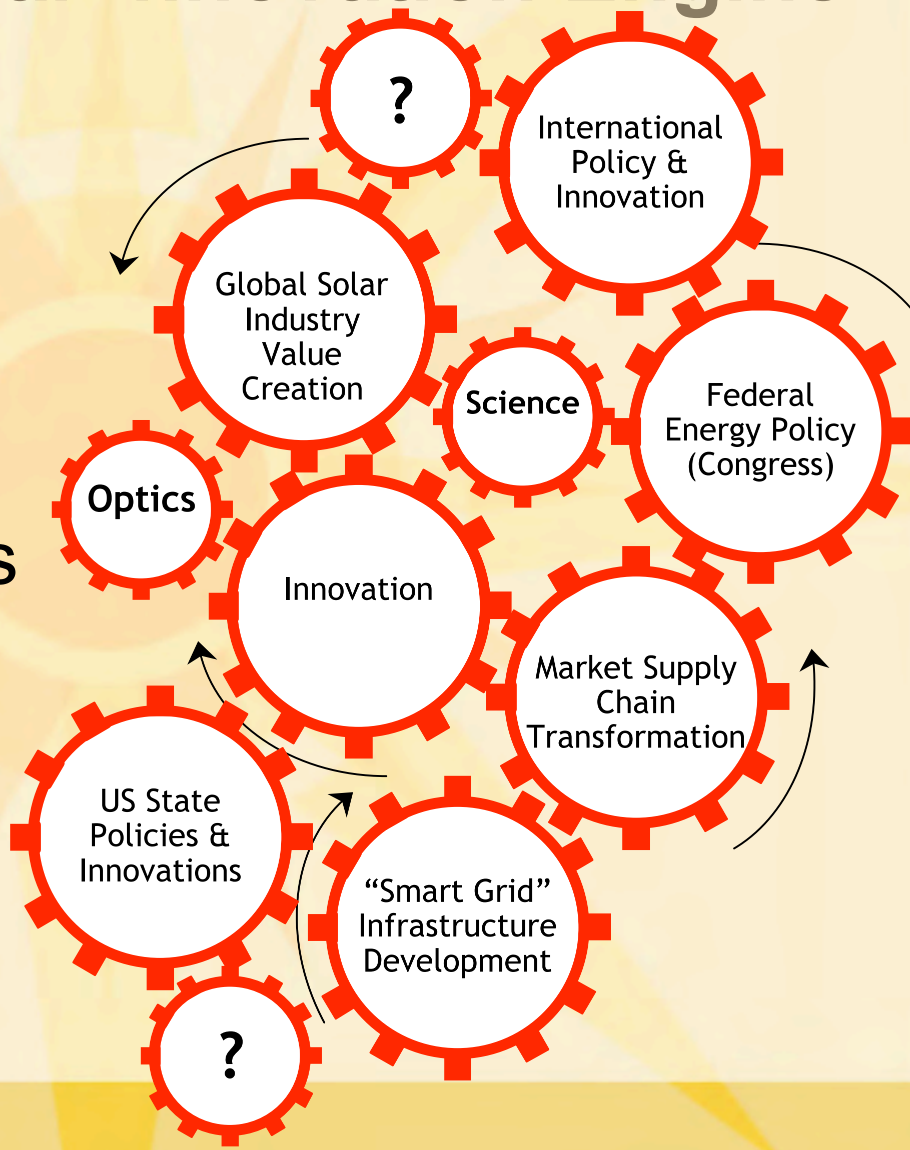
Senge Diagram —
System-Focused Solar Industry Development



Courtesy: Joe Morabito, Alcatel-Lucent, DOE/SETP March 2009

Powering the Solar Innovation Engine

- Interconnected ***systems*** reinforce the innovation process.
  - Positive Reinforcement spins the wheels faster!
- Feedback loops create virtuous cycles.



Conclusions

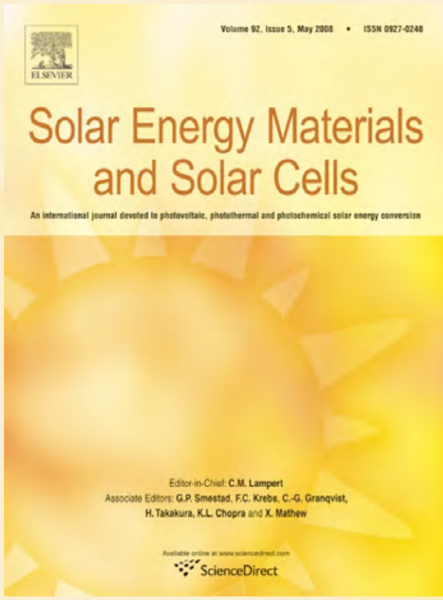
- Solar Cells can be viewed from a purely optical perspective.
- Solar Energy R&D and Industry Drivers should be considered in the context of **Systems Thinking**.
- Such perspectives lead to a multidisciplinary, collaborative approach.
- This can reduce the product development interval and facilitate technology transfer to more rapidly spin the Solar Innovation Engine.

Solar One: Courtesy NREL

Nellis/SunPower: Courtesy NREL

Thank you

Visit **http://www.solideas.com/** for further information, references and links.



SOL IDEAS TECHNOLOGY DEVELOPMENT

Greg P. Smestad, Ph.D.
Solar Energy Materials and Solar Cells
Sol Ideas Technology Development

OSA Science Educators Day

Thursday, October 15, 2009

5:30 p.m.-8:00 p.m.

McCaw Hall, Frances C. Arrillaga Alumni Center, Stanford University

326 Galvez St.

Stanford, CA

Tel.: +1 650.723.2021

Solar Cell Educational Kits

www.frontiersinoptics.com/SpecialEvents/default.aspx

Questions & Answers

- How does the Systems Approach in the Senge Diagram relate to OSA?
  - ✓ OSA is one of many organizations that feed in to the policy and supply chain aspects of PV. One recommendation from the approach is collaboration, coordination and integration between such organizations.

Questions & Answers

- With PV technologies and systems so diverse, how can the Systems Approach be used?
  - ✓ All installed PV systems must adhere to national and international standards of performance, longevity and stability. Earlier PV technologies can set the stage for new solar technologies as they enter the market.

Questions & Answers

- How was the approach developed?
  - ✓ It was developed by several reviewers for DOE, but does not represent the views of the U.S. Department of Energy.
  - ✓ We developed this analysis by substantial participation in the DOE Solar Energy Technologies Program's 2009 Annual Program Peer Review held in March, 2009.
  - ✓ More information is available (in the Past Meetings section) on the DOE website at: www1.eere.energy.gov/solar/review_meeting/