THE MIT *FUTURE OF SOLAR ENERGY* STUDY: EMERGING HIGHLIGHTS(?)

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What is the MIT Future of Solar Study?

- The latest in a series of MITEI interdisciplinary engineering + science + economics “Future of…” Studies:

- These aim to give a credible factual basis for decision-making

- Mainly critical surveys of the literature with some new work <u>plus policy recommendations</u>; have largely a US focus

Where Does The Solar Study Stand?

- A large team (many from Comillas!) have been at work for several years
- Much of the analytical work is done, almost-complete draft reviewed by an outside advisory committee
- Still have some unresolved disagreements & loose analytical ends, and writing needs considerable work
- Expect final manuscript around September 1, aim for publication in late fall (after the US elections…)
- I will present what I believe will be highlights of the things on which I hope we reach final agreement, though this talk will NOT be a perfect predictor of the final product

What's In The Study (& This Talk)?

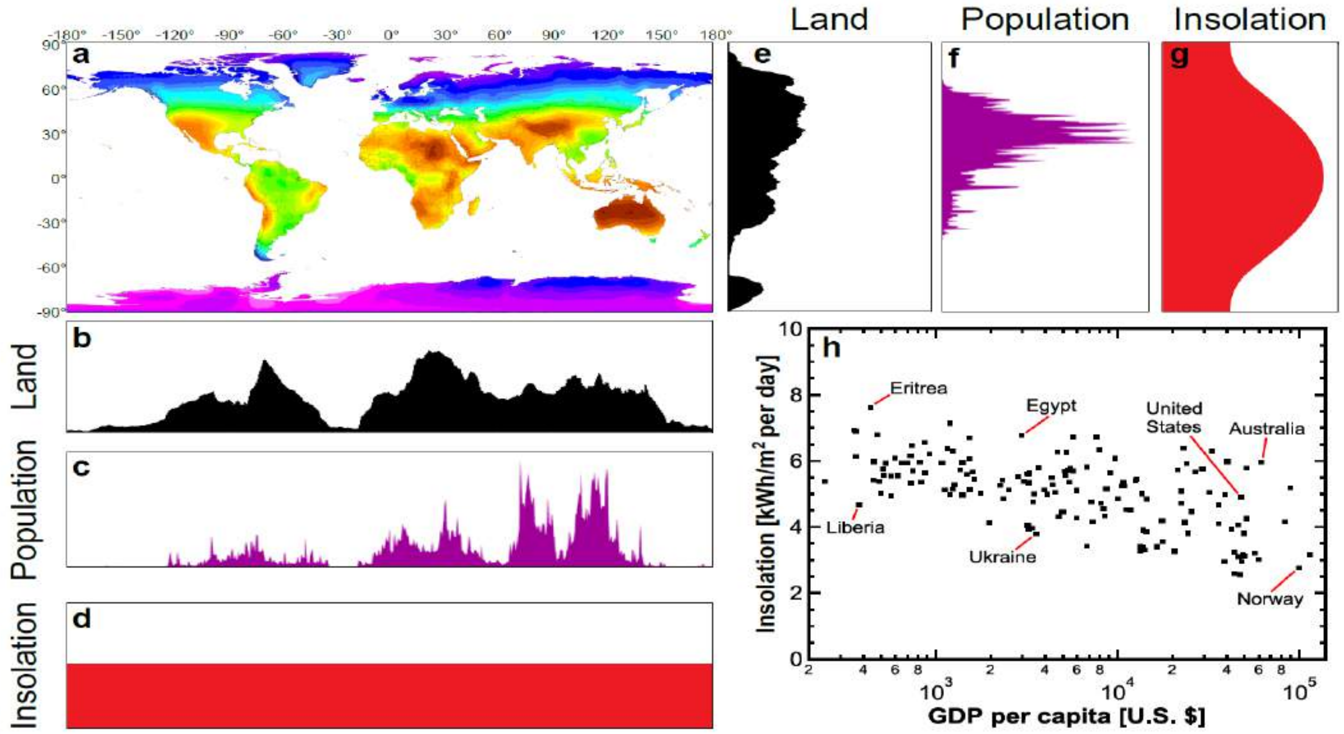
- Introduction
  - Motivation, Framing
  - The Solar Resource
- Solar Technologies (Appendices on Fuels, Hot Water, Storage)
  - Photovoltaic Technologies
  - Solar Thermal (CSP) Technologies
- Business/Economics
  - Business Models/Balance of System
  - Basic Economics
- Scaling & Integration Issues
  - Scaling Issues/Problems
  - Distributed Generation
  - Utility-Scale Generation
- Policies to Promote Solar Energy
  - Policies to Promote Deployment
  - Research, Development, & Demonstration

Introduction: Motivation & Framing

- To substantially reduce global CO_2 emissions will need substantial reductions in emissions from electricity generation
  - Perhaps electrify surface transportation; need solar to fuels (*appendix*) to reduce emissions from aviation; neither looks easy
  - Solar hot water (*companion paper*) may make a contribution, but the technology is mature & thus less interesting…
- The scale of the solar resource (later) makes it almost uniquely suited to play a major role in a low-carbon electricity sector
  - Nuclear can also scale, but polls badly; wind is the other contender
  - Lots of solar &/or wind would require lots of storage (*companion paper*)
- We thus focus on solar to electricity – with a concentration on the developed world, particularly the US – and on PV and CSP
  - In developing regions (*companion paper*) without grids, solar can provide small amounts of power (lanterns, village nets) with value above cost
  - In developing countries with hydro (Kenya), using solar to back out diesel may make sense

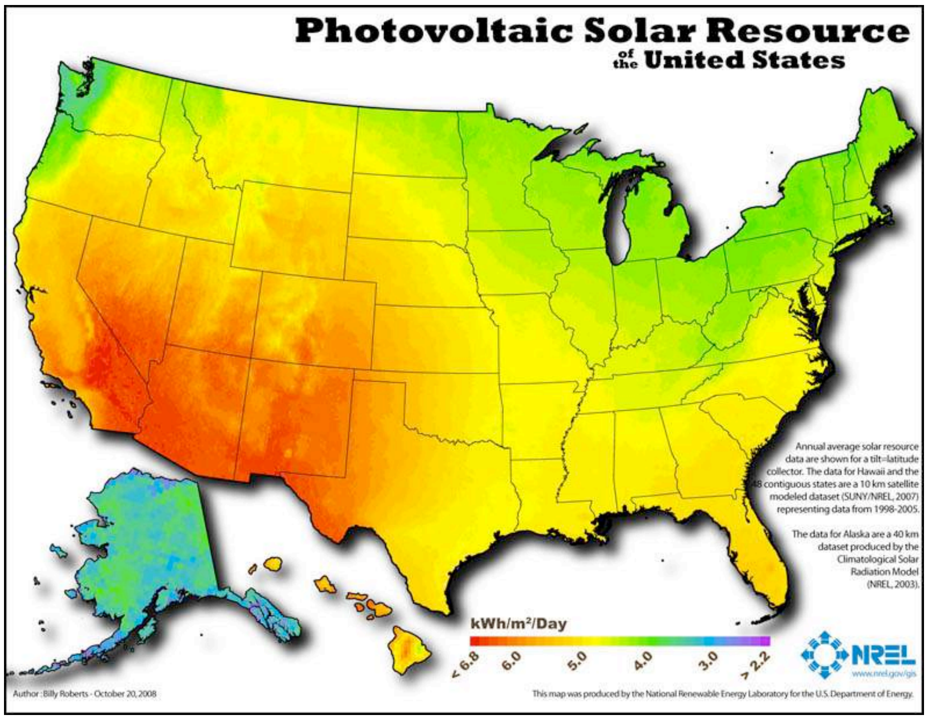
Introduction: The Solar Resource

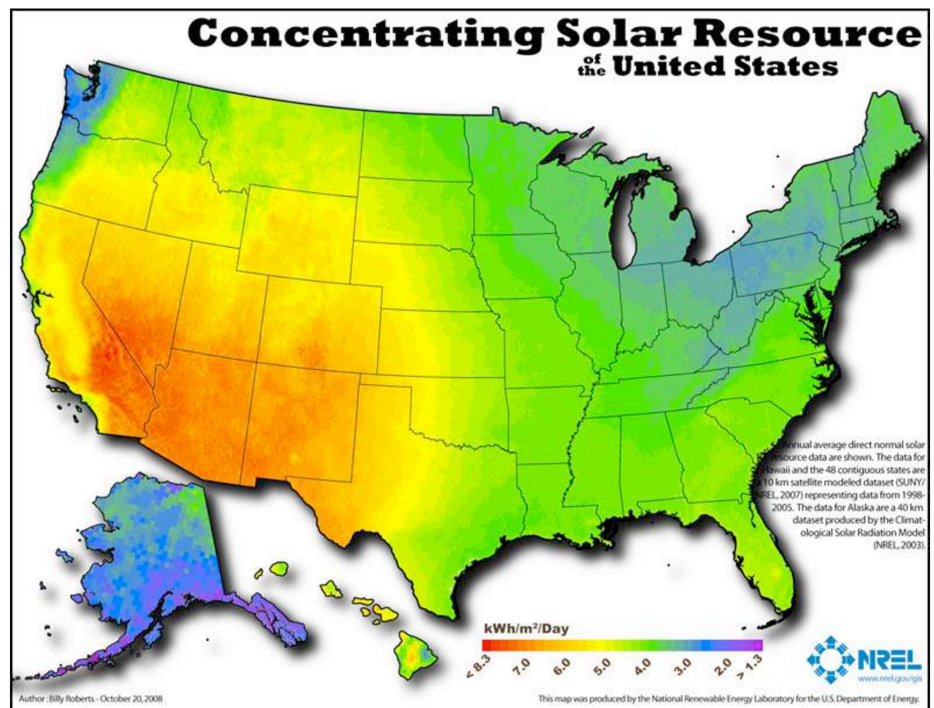
- It is **enormous**: At the average insolation of the continental US, it would take only 0.6% of land area to generate MWh equal to total consumption
  - About the same as major roads, less than land used for corn ethanol
- It is relatively "equitably" distributed globally:



Introduction: The Solar Resource

- But within countries, good sites for CSP (direct radiation only) and PV (all radiation) may be far from load, & transmission is hard to build

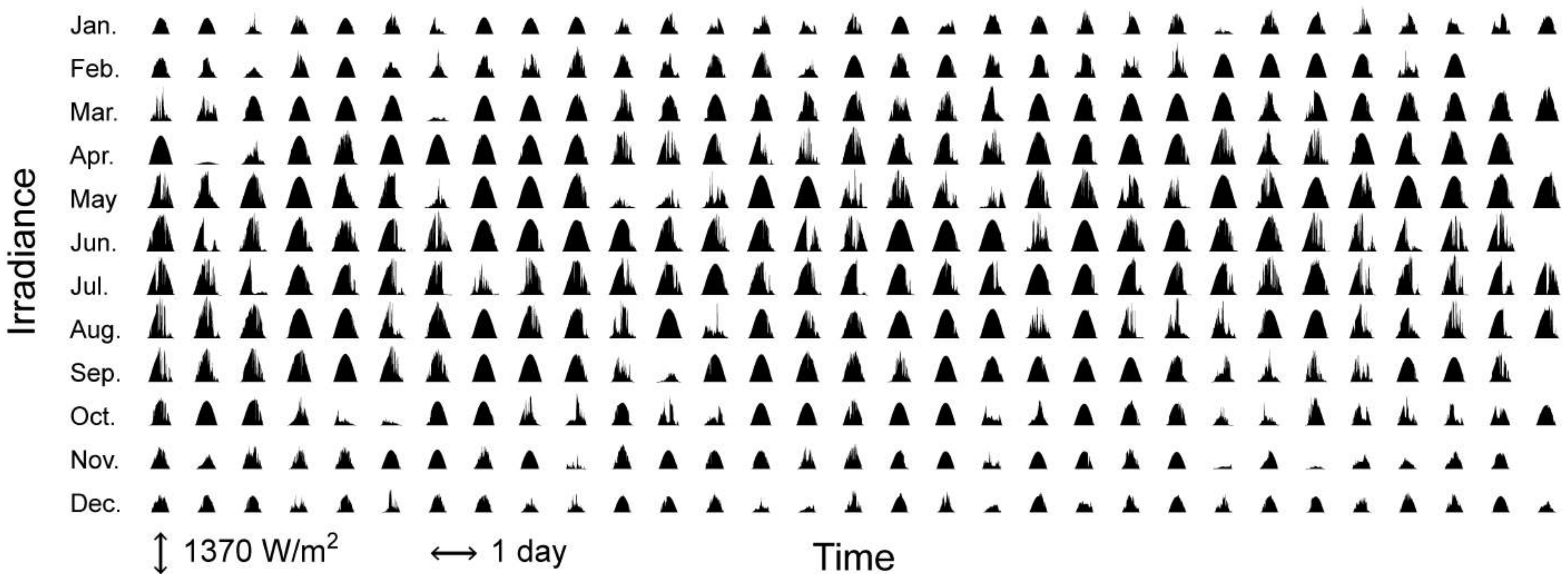




- A problem for some countries

Introduction: The Solar Resource

- And irradiance is intermittent: variable and imperfectly predictable
  - E.g., Golden Colorado in 2012



- Intermittency is a major problem everywhere (as is cost)

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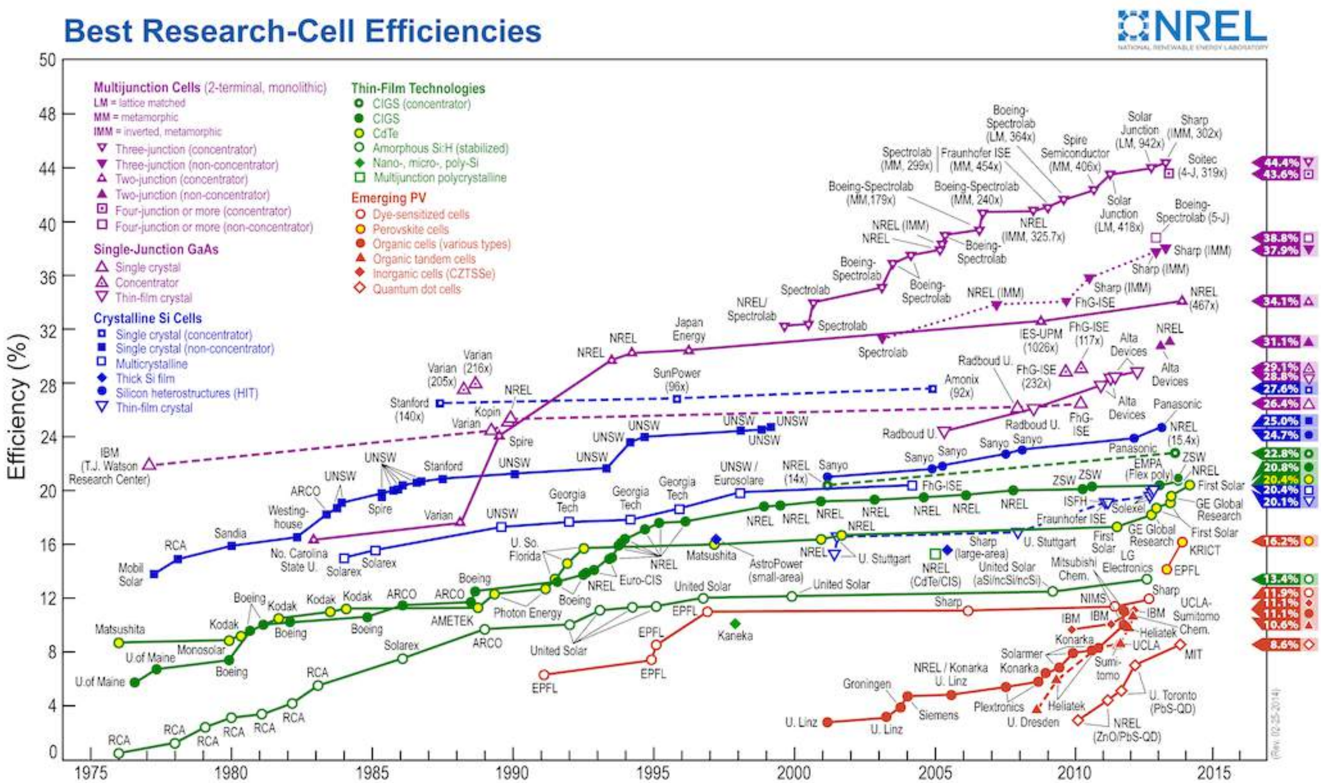
Solar Technologies: Photovoltaics

- Systems consist of modules with multiple cells, inverters (to produce AC), brackets, and associated wiring
- Big advantage: module efficiency does not depend on facility scale; great for no-grid regions, some applications
- But no storage, though geographic averaging can mitigate short-term fluctuations (clouds)

Solar Technologies: Photovoltaics

- Many different photovoltaic technologies have attracted researchers' attention over the years:



- Efficiencies in the field are considerably lower than in the lab…

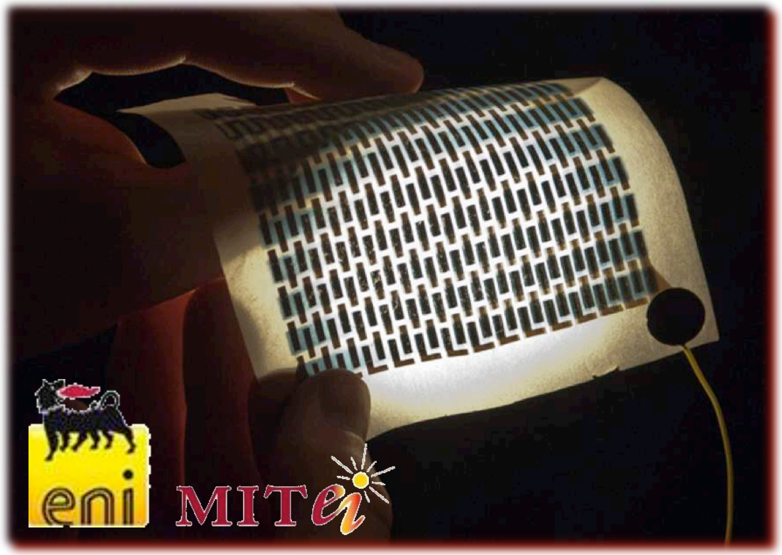
Solar Technologies: Photovoltaics

- Crystalline silicon cells, the most mature technology, have about a 90% market share
  - Demonstrated in 1954; launched into orbit in 1958
  - China has dominated module manufacturing in recent years, but the associated supply chain is global
  - Expect silicon to dominate for some time to come; manufacturing is advancing, no challengers ready for large-scale deployment
- Thin-film technologies have about a 10% share
  - Less efficient, so more area & BOS per kWh; less materials use
  - Some current technologies use scarce materials that will make large-scale deployment difficult at best (later)
- Some new thin-film technologies have novel properties that may enable them to attain scale via dominating niche applications (**engineers' slides follow…**):

MIT PVs on Paper

Watts/kg

(important metric that is often ignored & can be <u>transformative</u> for developing world)



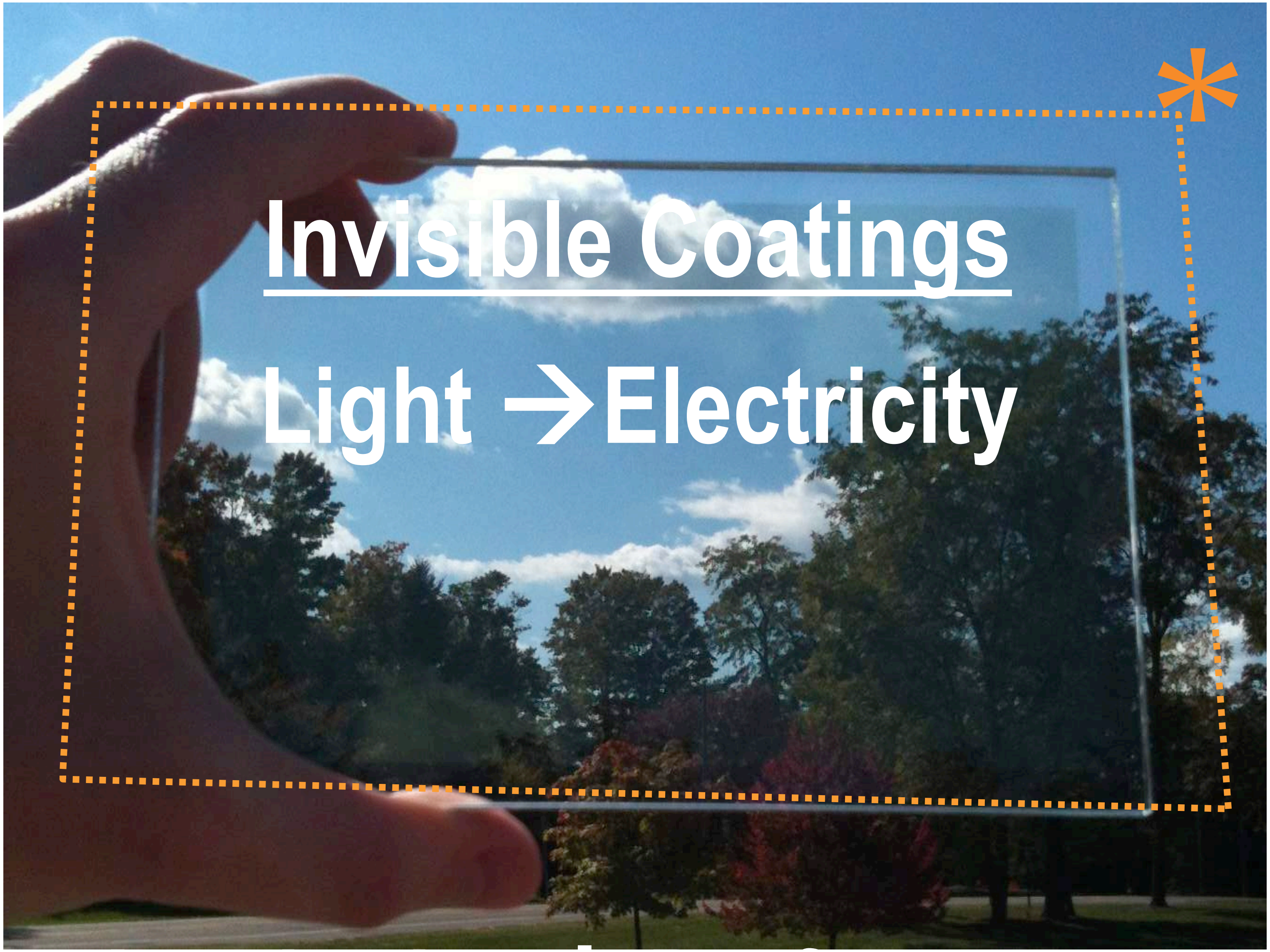
PAPER

- Displays *printed content*
- Packages *physical content*
- Cheap, disposable, lightweight
- **PASSIVE**

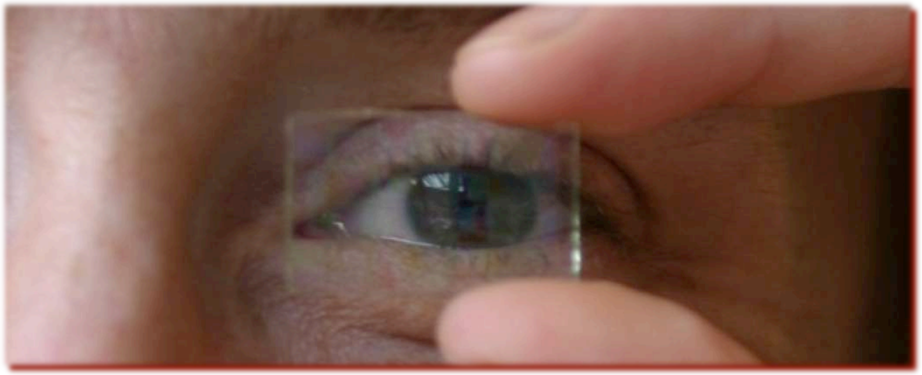
ENERGY EVERYWHERE

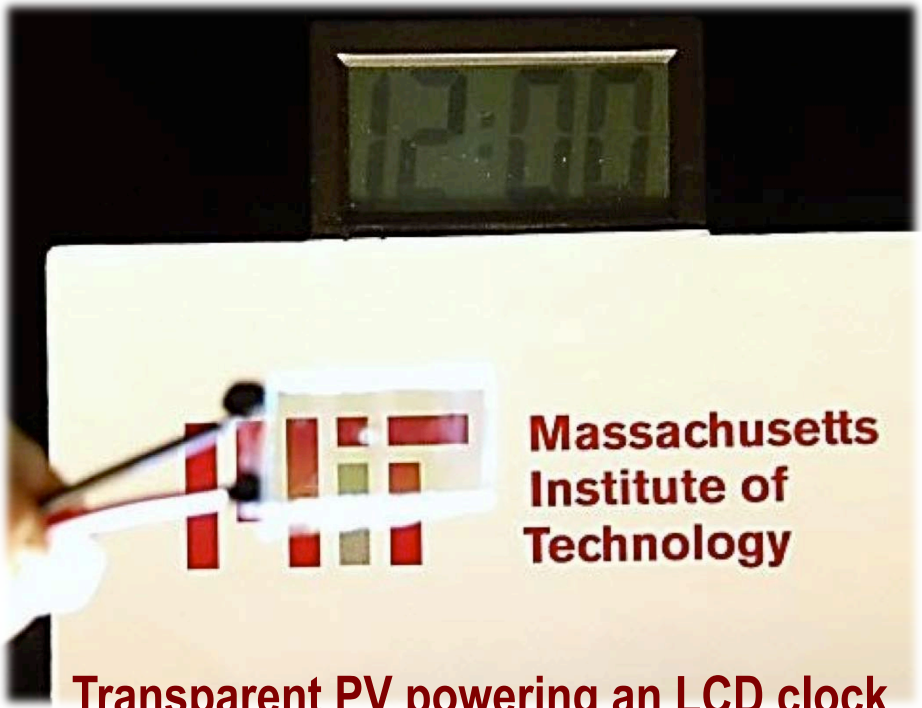
Transforms paper products into an energy source: **ACTIVE** functionality

- Invisible solar cell film
- Compatible w/ printed content
- No added weight
- Flexible and foldable


Invisible Coatings
Light → Electricity

Transparent PVs





Transparent PV powering an LCD clock

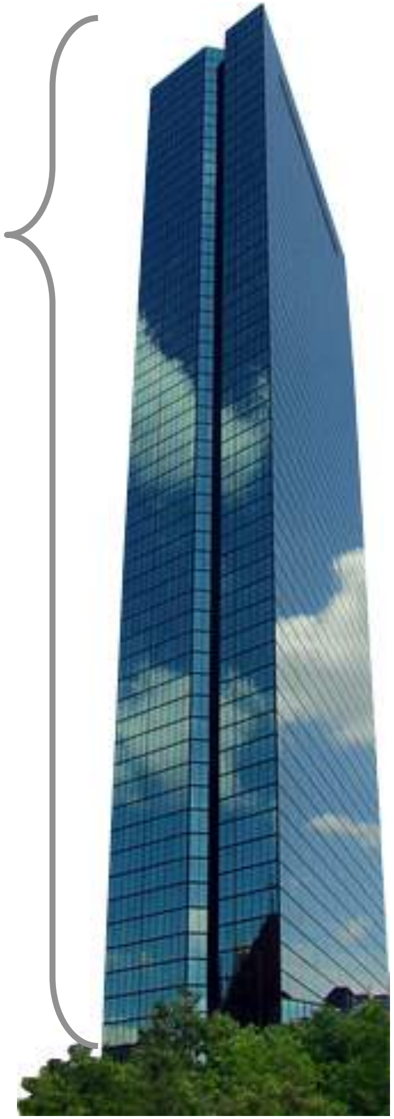
energy independence at any scale

Hancock Tower
Boston, MA

>500,000 ft^2

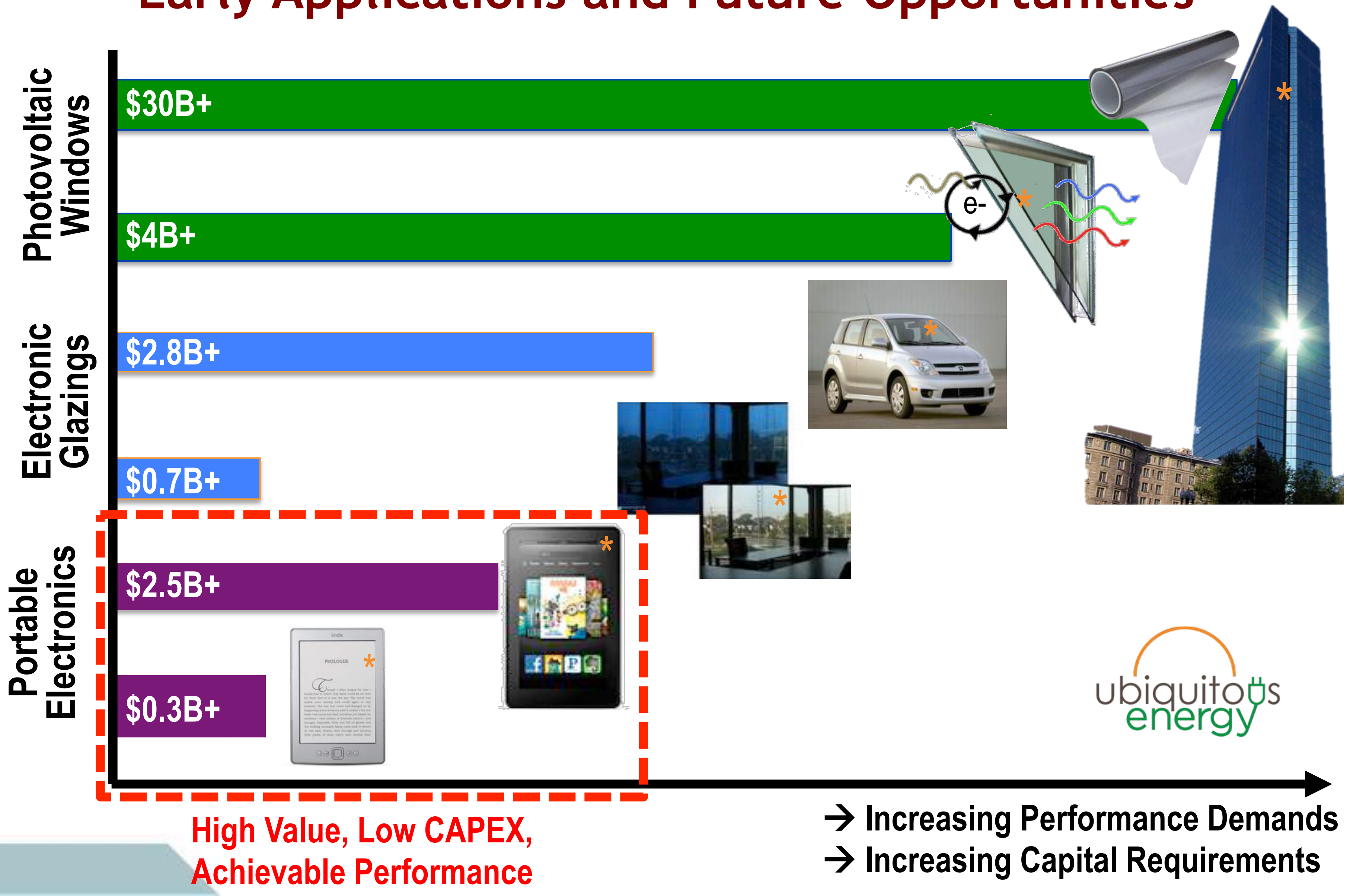
Portable Electronics
Everytown, USA

<1 ft^2



Lunt & Bulovic, Applied Physics Letters, vol. 98 (2011)

Transparent PVs
Early Applications and Future Opportunities



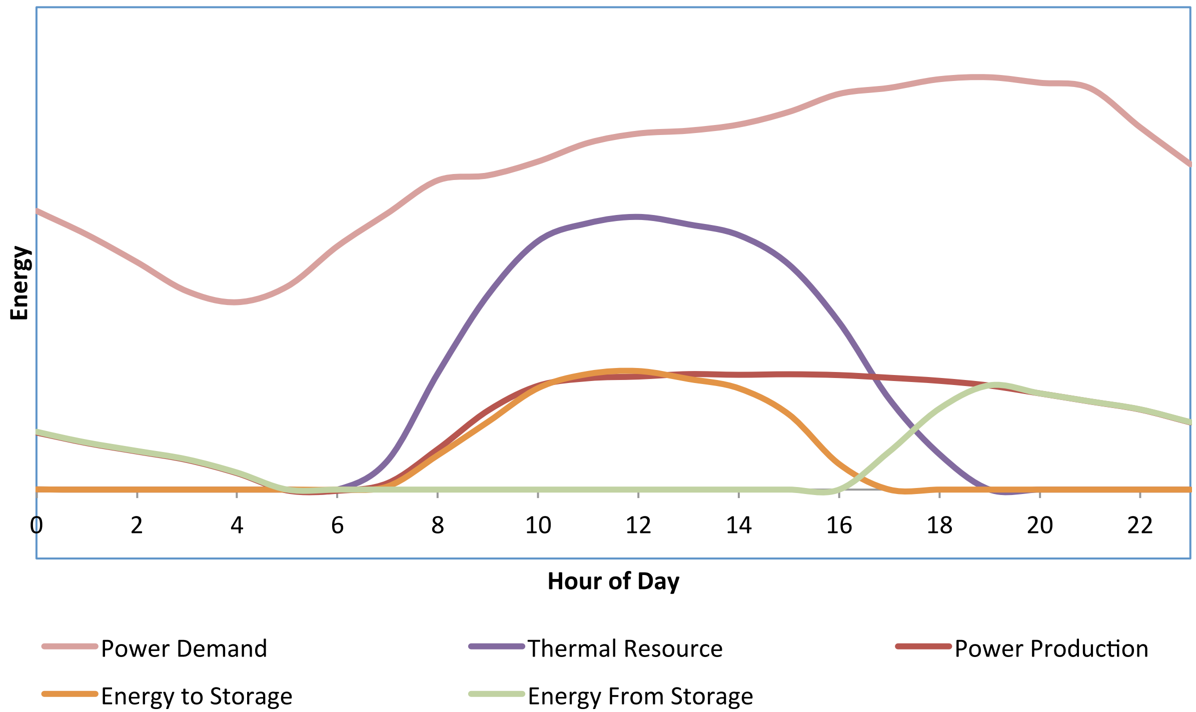
Solar Technologies: Solar Thermal (CSP)

- Heat a working fluid; use it to produce steam that drives a turbine
- Needs large scale & can use only direct radiation (no haze), limits sites

- Trough technology is proven, but power towers probably have more long-run potential because of higher temperatures & thus efficiency
- Both have higher LCOE (not a sufficient statistic!) than PV today

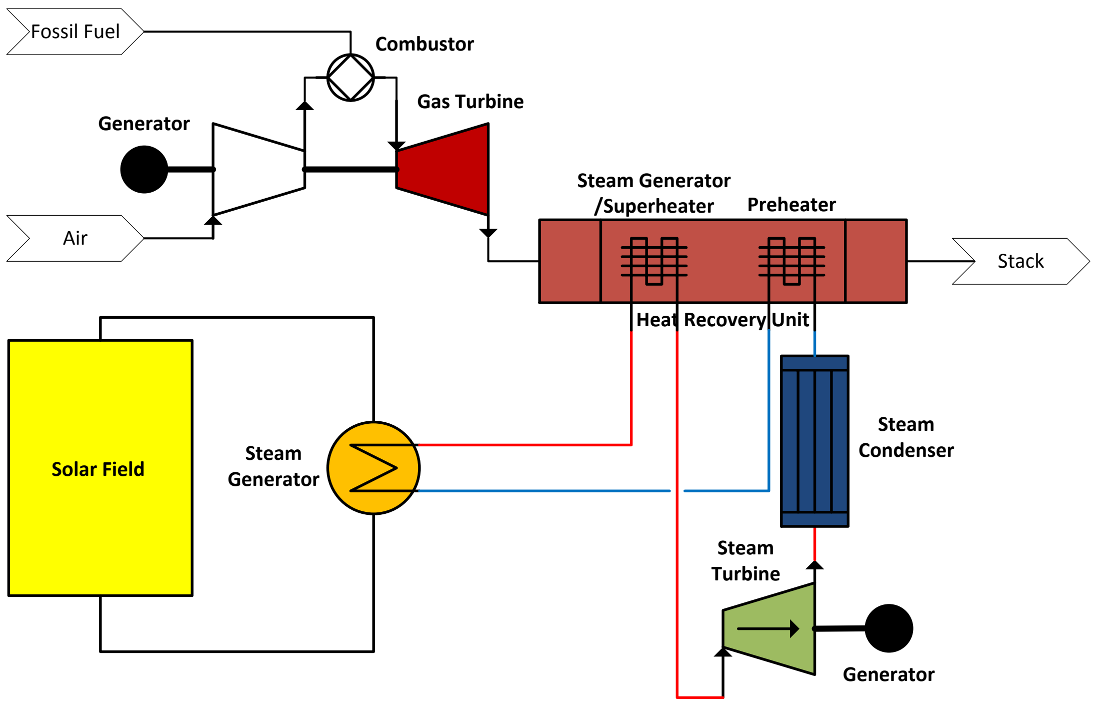
Solar Technologies: Solar Thermal

- Advantage: CSP lends itself to highly efficient thermal storage (over hours) that smooths output, lowers costs (via constant turbine operation), & makes CSP somewhat dispatchable



Solar Technologies: Solar Thermal (CSP)

- Advantage: CSP can easily be hybridized with natural gas via the common turbine; this increases dispatchability & provides a migration path from fossil energy in regions where CSP is a sensible choice



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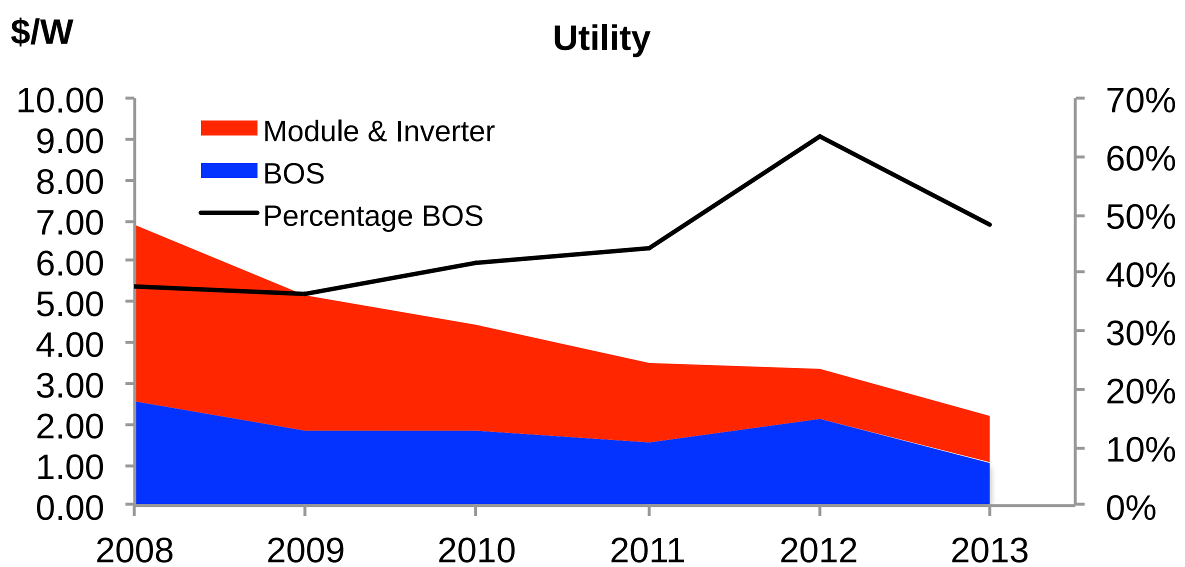
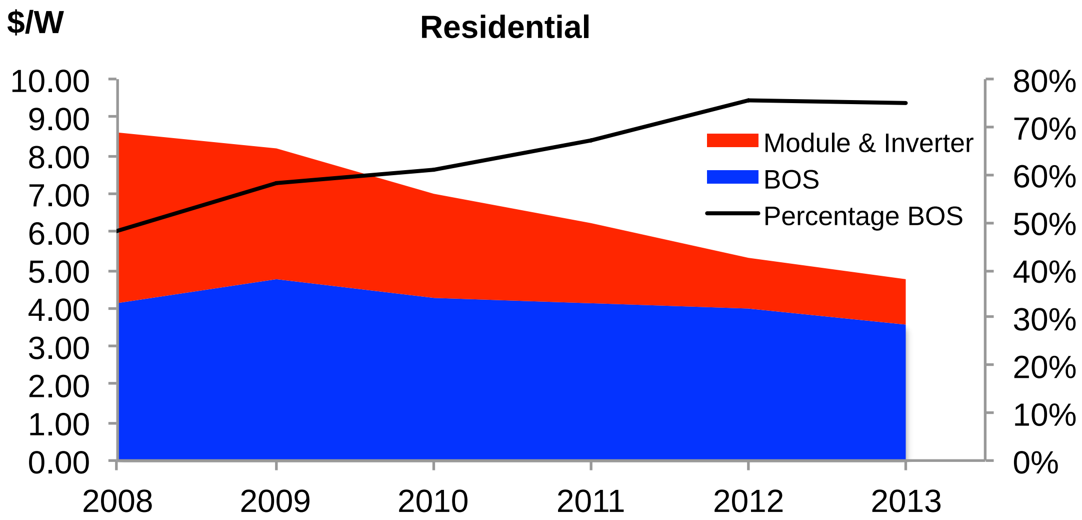
Business/Economics: Business Models/Balance of System

- Part of this chapter will discuss why rooftop solar has become so popular in the US, particularly California: weird retail rates, net metering, investment tax credits, and clever marketing…
- Also studies (available) system costs, backing out commodity module & inverter costs to get "Balance Of System costs"
  - Module cost decline: manufacturing progress + huge Chinese overcapacity
- Some decline in BOS costs for utility-scale systems, about 50% of total



Business/Economics: Business Models/Balance of System

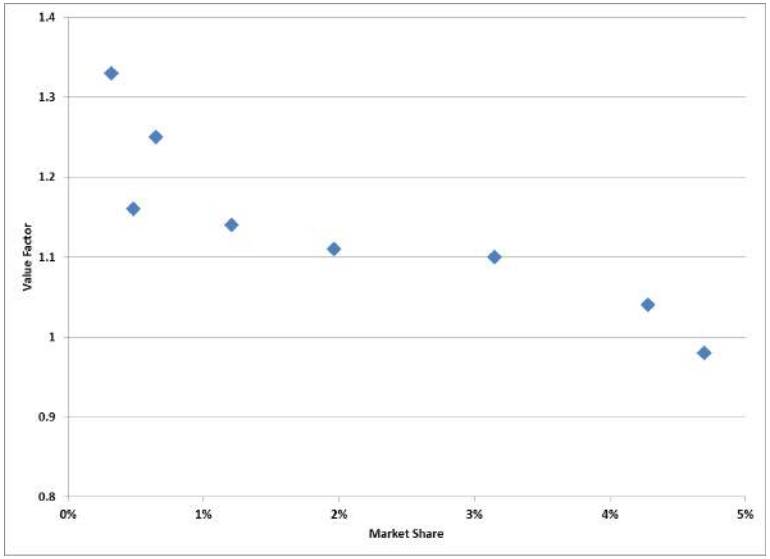
- But residential-scale BOS is much higher than utility-scale – and than German costs, not declining, and dominates system cost:



- Multiple causes; hard to quantify impacts:
  - Less-informed US customers raise customer acquisition cost
  - Relatively small scale & inexperience of US installers raise labor & materials cost
  - State/local policies raise permitting, inspection, and interconnection costs
  - Thin markets, less competition, and rents to vendors

Business/Economics: Basic Economics

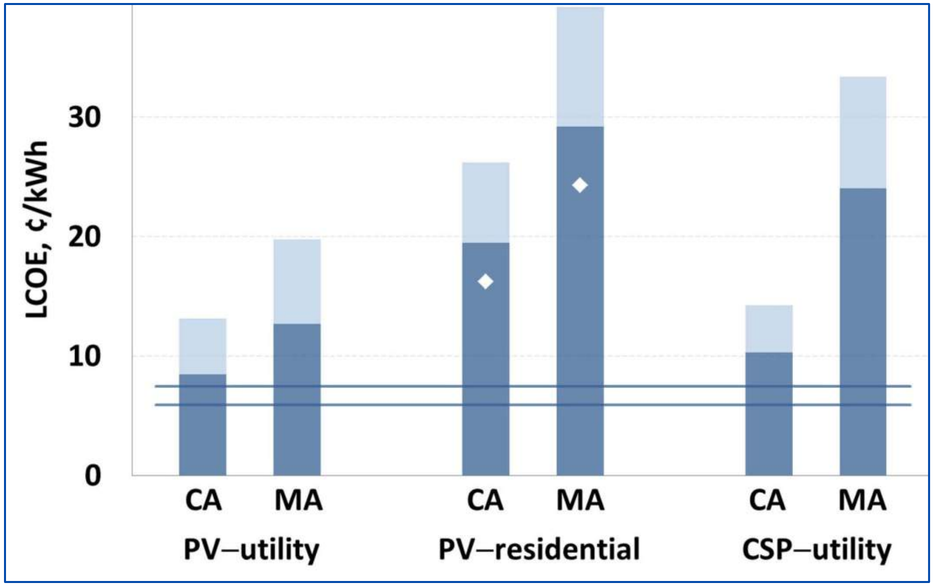
- This chapter goes from capital costs to LCOE, looks at impact of subsidies, regional (California-Massachusetts) differences in radiation
  - Raw LCOE clearly not a sufficient statistic for non-dispatchable resources
  - Adjusting for variation in *current* spot prices gives solar a 10-13% premium
  - But more solar will erase this premium, as it has done in Germany (Hirth):



  - And integration costs are beyond the scope of this chapter

Business/Economics: Basic Economics

- Graph shows unadjusted LCOEs (actual PV prices, modeled CSP costs), with a range of CCGT estimates for comparison
- Location (sunshine) matters, especially for CSP
- Federal subsidies matter – light v. dark bars; state/local would add
- Residential PV is much more expensive than utility, even with plausible reductions in BOS costs (white diamonds)



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Scaling & Integration Issues: Scaling

- For solar energy to play a major role in the global energy system by mid-century, the industry and its suppliers (esp. materials) will have to scale up dramatically – as likely will suppliers of (some sort of) storage
- To get some quantitative sense of what's required I took
  - US EIA: global solar generation & capacity in 2010 (PV & CSP), projected total global generation in 2040 (2.21% CAGR from 2010)
  - REN21 2014 Report: 39.9 GW installed in 2013, year-end capacity 132.4 GW
- Suppose solar is to account for 20% of 2040 generation and will operate with the 2010 EIA global capacity factor
  - Will need 8,500 GW in 2040, 64 times year-end 2013 capacity
  - If solar facilities last 27 years, will need to build 8,630 GW over 27 years plus replace year-end 2013 capacity: average 320 GW/year, 8 times the 2013 installation rate
  - Can be accomplished if installation grows steadily at 12.4% per annum over the entire period. Is this realistic?

Scaling & Integration Issues: Scaling

- Important scaling issue: Some *materials* being used in solar technologies that have been deployed at small scale are likely to become much more expensive as a consequence of large-scale deployment

- 10% of silver production is now used in silicon-based solar sells; scaling up production would likely increase costs

- The leading thin-film technologies use elements that are on criticality lists: gallium, indium, selenium, and tellurium
  - All are produced as by-products of primary production of a major metal
  - High deployment rates would require attempting primary production, with potentially huge increases in cost
  - The case of tellurium is particularly striking …

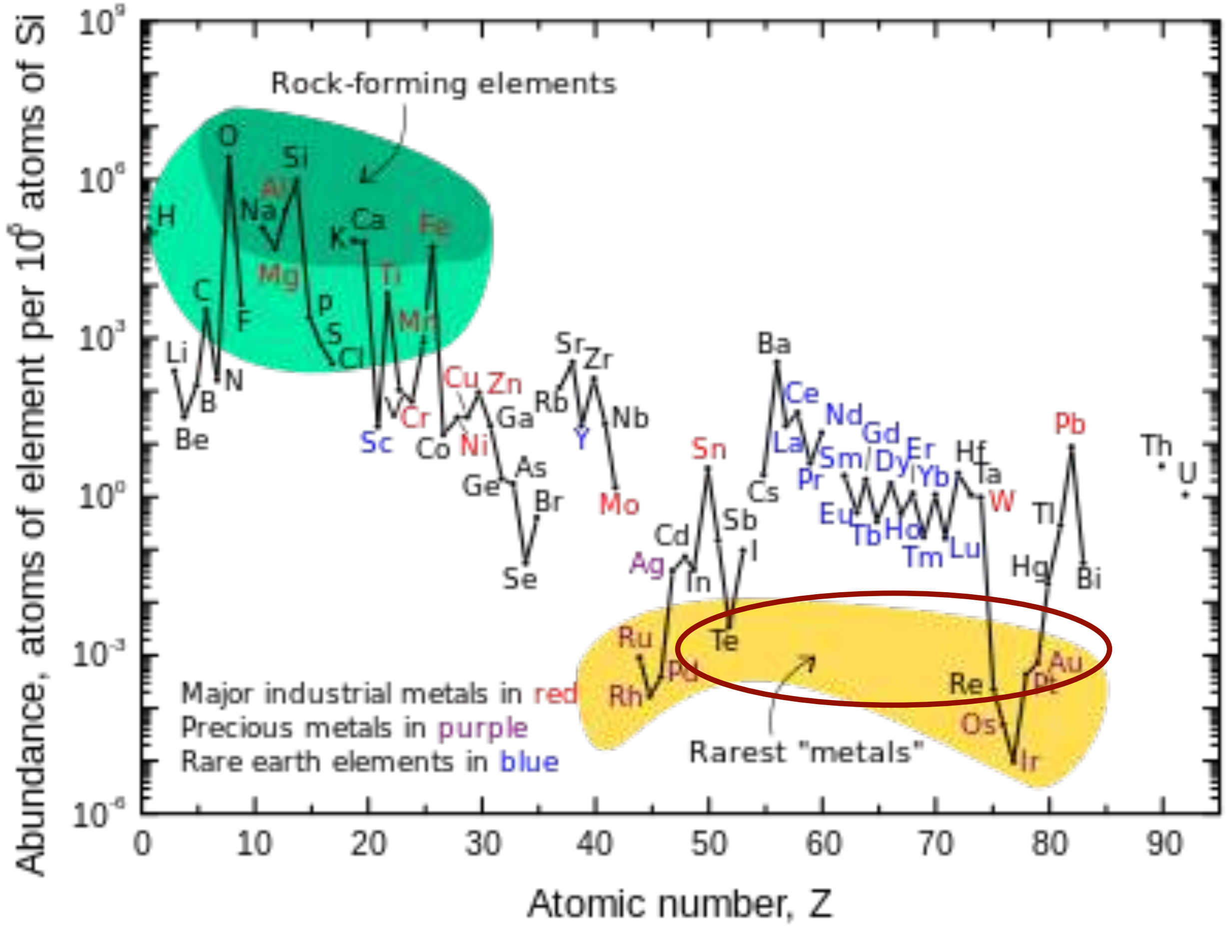
Scaling & Integration Issues: Scaling

Tellurium is roughly as abundant as gold or platinum(!)

Currently a by-product of copper refining; no primary production

Large-scale CdTe deployment would use a large multiple of current production

Material abundance should affect choice of technologies for R&D!



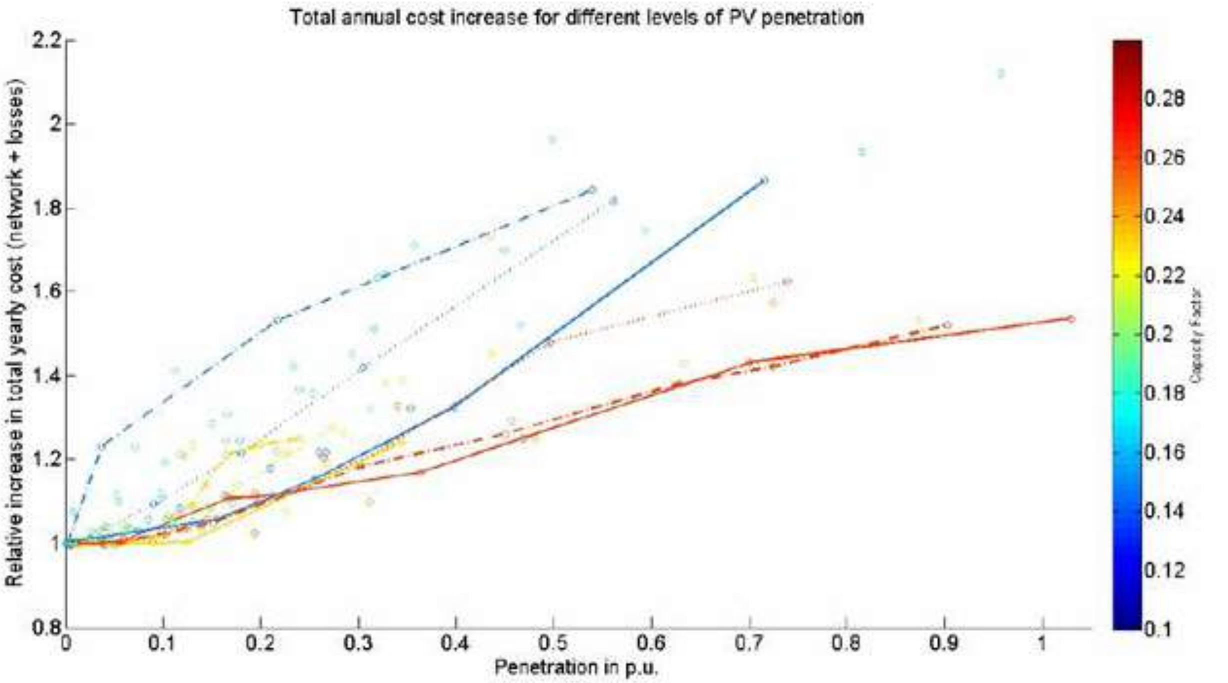
Scaling & Integration Issues: Distribution

Method: In multiple locations around the US, "built" model networks to serve load, then added distributed generation and examined changes in capital & operating cost

At low levels of penetration, very little impact

When some areas become net generators, need to modify network to maintain service quality, esp. tosatisfy *voltage limits*

This swamps any gains from reduced line losses



Scaling & Integration Issues: Utility-Scale Generation

- Simulated addition of solar to California-like and Texas-like markets; Texas has much less hydro
- Adding PV to an existing system (*some of many results*)
  - Pushes high variable cost plants out of the market
  - Increases thermal plants cycling requirements – esp. with little hydro
  - Increases ramping requirements for thermal plants
  - Will eventually reduce the per-kWh revenue of solar plants
  - May make it efficient to curtail solar to avoid cycling thermal plants
  - May not reduce the need for thermal capacity, since peak load may occur well after peak solar generation
- Systems with more hydro or CSP with storage handle PV better

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Policies to Promote Solar Energy: General

- The market-failure-based rationales for promoting solar:
  - Usual spillover rationale for supporting R&D, with a pro-solar bias (of some sort) justified by solar's potential for scale-up
  - Deployment support can be rationalized as a second-best environmental policy (vs. a price on carbon, other pollutants), especially as regards climate change
  - There is no energy security case in the US; may be one in the EU
- Barriers to the diffusion of solar technology or to trade in products in the solar value chain make it harder to achieve environmental goals
- Given limited budgets, a balance must be struck between spending to deploy today's expensive solar technology and spending to reduce the cost of tomorrow's solar technology
  - Most of us lean toward R&D, but there is no consensus on the balance, and R&D is more effective when there is a potential market payoff

Policies to Promote Solar Energy: Deployment

This section is mainly a critique of the current fragmented US policy regime:

- Particularly in the US, where average residential BOS costs are likely to remain high, subsidizing residential solar more than utility-scale solar makes no sense at all!
- Investment-based subsidies, particularly those that take the form of tax credits, are less efficient than price- or output-based subsidies
- Among price-based subsidies, direct payments are more efficient than tax credits, and premium feed-in tariffs provide better incentives for producing power when needed than flat feed-in tariffs
- A nationwide RPS program that permitted unlimited interstate trading would be more efficient than the existing state programs
- Net metering provides a hidden subsidy to residential solar at the expense of either utility shareholders or other customers

Policies to Promote Solar Energy: RD&D

- This chapter is still in fairly rough form; we have (easy) agreement on some broad themes but not yet on all details
- Given the high cost of solar today and the likely need to deploy it at large scale in the future, government research, development, & demonstration should focus on reducing future costs
- Thus RD&D programs should aim to produce significant advances that can lower costs substantially, not incremental improvements on current technologies, and funding should be stable
- A few specific points of agreement:
  - Don't need huge levels of spending if focus on basic research & stablize
  - Solar to fuels & grid-level storage are far from commercial; good targets for basic research spending
  - In PV, marginal increases in module efficiency are less important than reductions in BOS costs
  - Focus should be on technologies that can scale, e.g., not Tellurium
  - In CSP, explore high temperature designs & material requirements

Thanks for Your Attention!

Look for the Solar Study in Late Fall:

http://mitei.mit.edu/publications/reports-studies