Pushing Solar Into the Grid

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Background: MIT Future of Solar Study

- What are the prospects and challenges for solar?
  - Study includes solar-electricity, solar-heating, solar-fuels; focus on electricity
  - By 2050, can solar make a significant contribution to energy needs?
  - Analyze technical and economic aspects of solar
  - Formulate policy and technology recommendations
  - This presentation will focus on the economics of solar electricity (PV,. CSP)

- The scale of the challenge
  - Solar accounts for far less than 1% of electricity production in the US
  - Current generation from solar in US replaces about 1 modest-sized coal plant
  - **But: solar has been growing very quickly and we won't run out of sunlight**

- MIT "Future of" Studies
  - Nuclear (2003) and coal (2007) reports
  - Ongoing natural gas study

Brief Overview of Solar Technologies

- Photovoltaic (PV)
  - Silicon (crystalline, amorphous)
  - Crystalline thin film (e.g., CdTe)
  - Other thin film, organics, etc.

- Concentrating Solar Power (CSP)
  - Parabolic trough (1)
  - Power tower (2)
  - Linear Fresnel
  - Stirling Dish

- Solar water heating, solar-fuels

(1) Kramer Junction

(2) Solar Two

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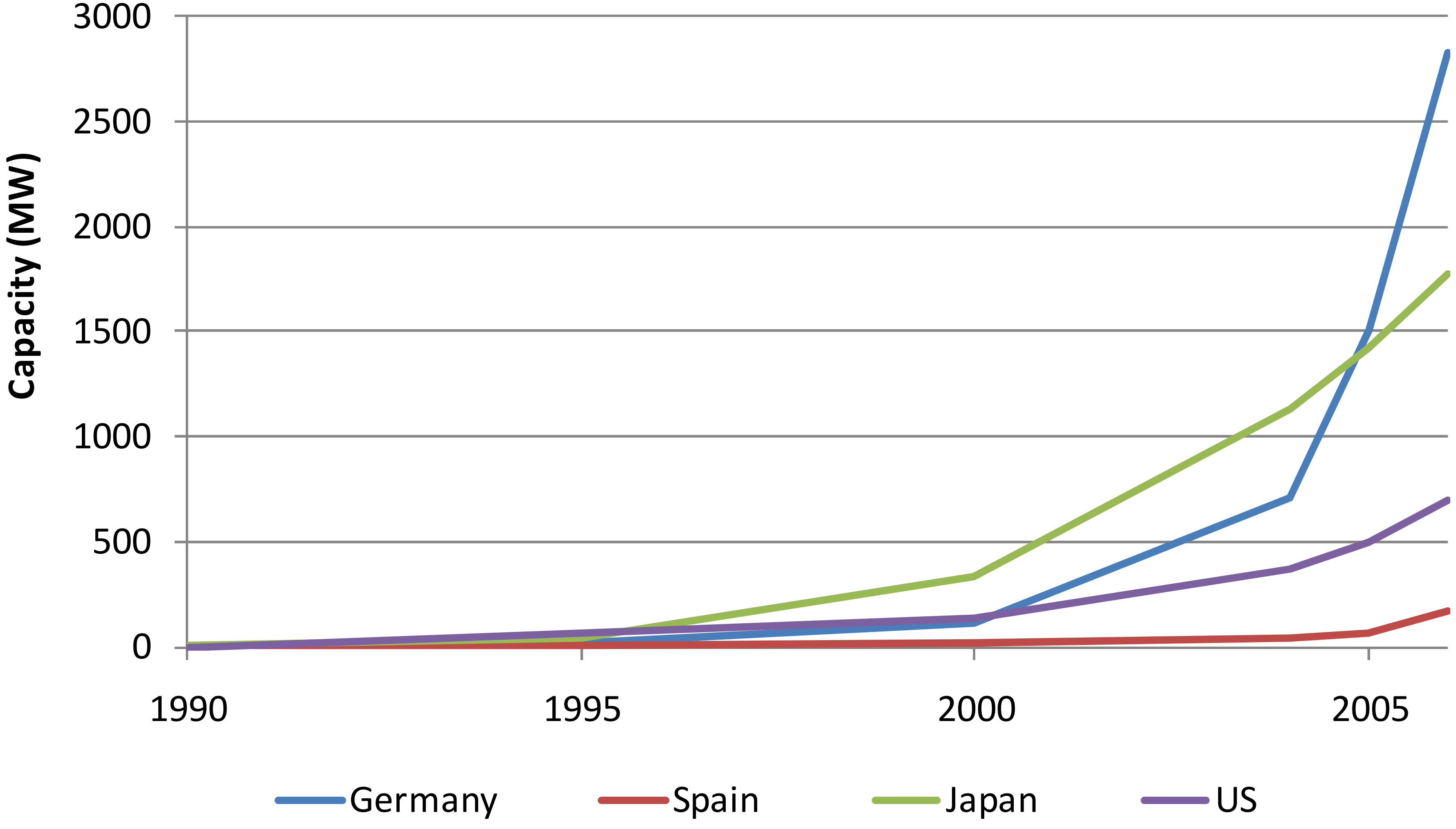
Figure 1: Cumulative Installed PV Capacity by Country, 1990-2006



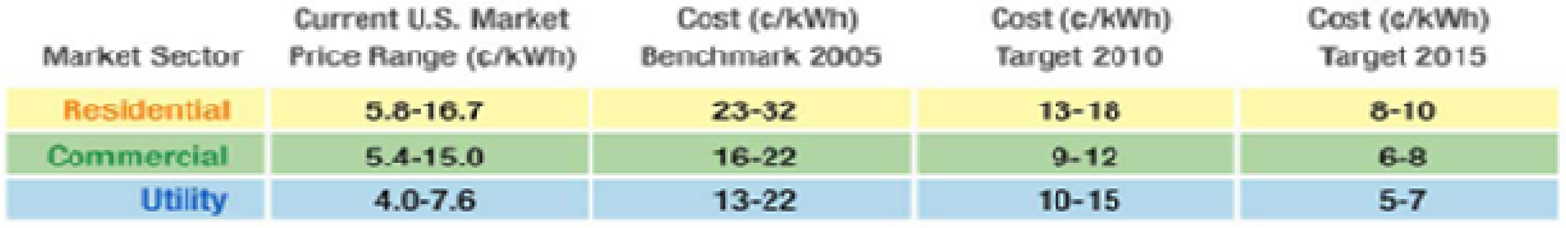
Source: IEA

A Sunny Picture for Solar?

- Compare levelized cost of energy (LCOE) of solar vs. conventional generation sources
  - LCOE is the price needed to cover costs
  - Roughly, total cost divided by total quantity
  - LCOE varies across conventional generation technologies and solar technologies

- Based on this picture, solar will take off within 5-10 years
  - Expect LCOE for conventional technologies to increase over time and LCOE for solar to decrease over time
  - Exponential growth after solar is competitive with conventional technologies

Figure 2: DOE Targets and Market Penetration



Market Sector	Current U.S. Market Price Range (c/kWh)	Cost (c/kWh) Benchmark 2005	Cost (c/kWh) Target 2010	Cost (c/kWh) Target 2015
Residential	5.8-16.7	23-32	13-18	8-10
Commercial	5.4-15.0	16-22	9-12	6-8
Utility	4.0-7.6	13-22	10-15	5-7

Source: US DOE

Is the Story So Simple?

- Where will costs go?
  - Steady decrease in costs over the past few decades
  - Considerable uncertainty about how low costs can go (Morgan *et al*., 2008)

- Solar is different from conventional technologies
  - Near-peak coincidence, but can’t dispatch without storage
  - Variability/intermittency
  - Environmental effects
  - Solar provides a different service from conventional technologies

- Comparing LCOE is not appropriate
  - Solar may not be able to contribute significantly even if LCOE is comparable to conventional base load
  - A more flexible framework is necessary

Analytical Framework

- Two stages to the analysis
  - Zero market penetration
  - Large-scale penetration (feasible by 2050)

- Zero market penetration
  - Put aside intermittency, transmission, etc. and assume no solar
  - Does it make economic sense to invest in the first solar plant?
  - Necessary condition for solar to make a significant contribution

- High penetration
  - What issues arise at high levels of penetration?
  - How serious are they?

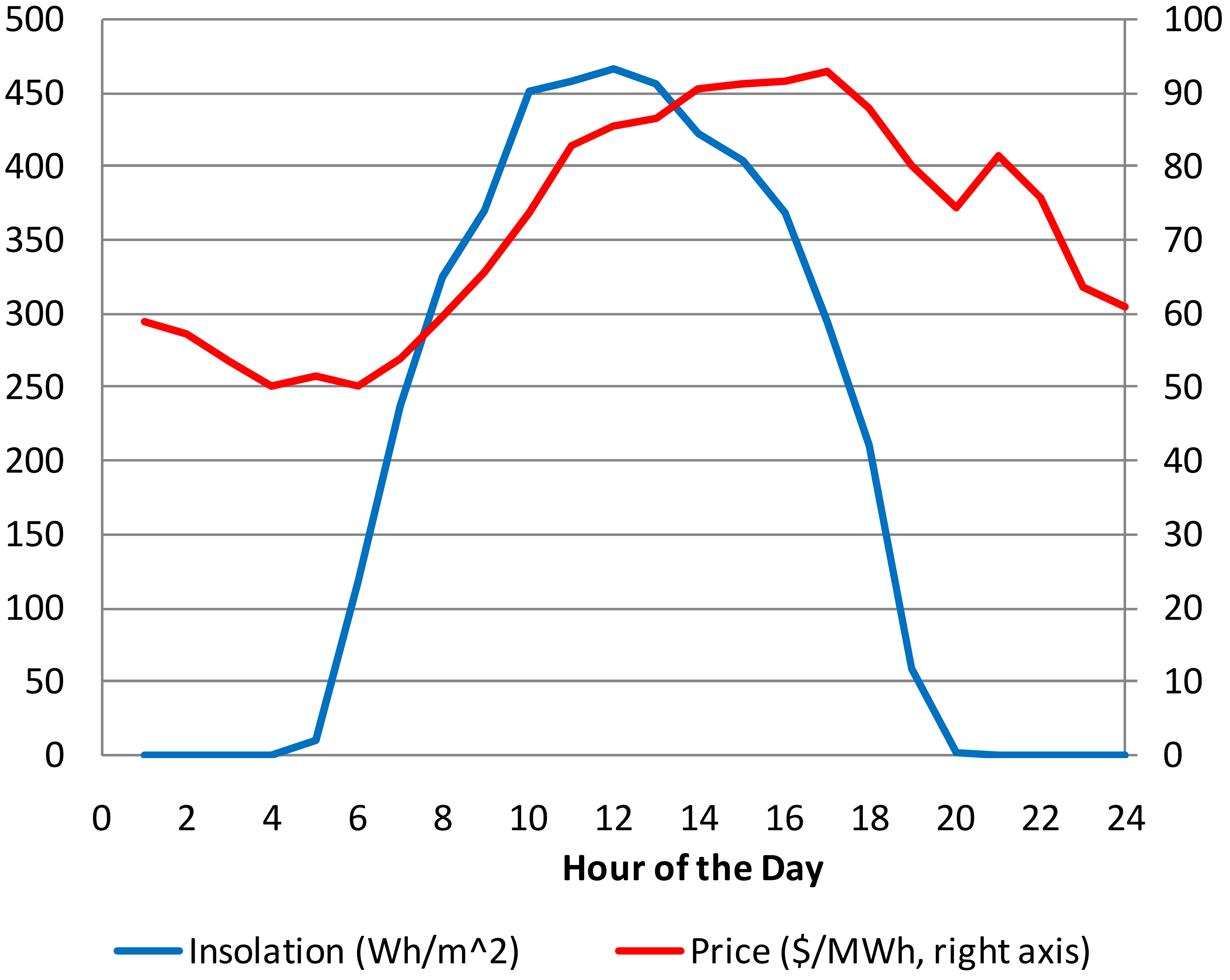
Zero Market Penetration

- Key assumptions
  - Starting from zero solar in market, consider a single solar system
  - Estimate costs and value using market prices
  - Include both private and social value (avoided carbon emissions)
- What drives the profitability of solar?
  - Analyze residential, commercial, utility scale systems
  - Estimate NPV of a system
  - Sensitivity analysis
    - Electricity prices and insolation
    - Carbon price
    - System costs
    - Discount rate and system life

Conclusions for Solar at Zero Market Penetration

- NPV < 0 for nearly all locations under baseline assumptions
- Solar is roughly peak coincident in most locations, replacing peaking/shoulder generation
- Electricity prices affect NPV more than insolation
  - Range of electricity prices is two times range of average insolation
  - Unexpectedly high energy prices could significantly increase NPV
- Moderate value of avoided carbon emissions
- Discount rate matters much more than system life
  - Extending life beyond 30 years has little effect due to discounting
  - Decreasing interest rate would increase NPV

Figure 3: Electricity Price and Insolation in Boston in July



Source: NE ISO and SUNY

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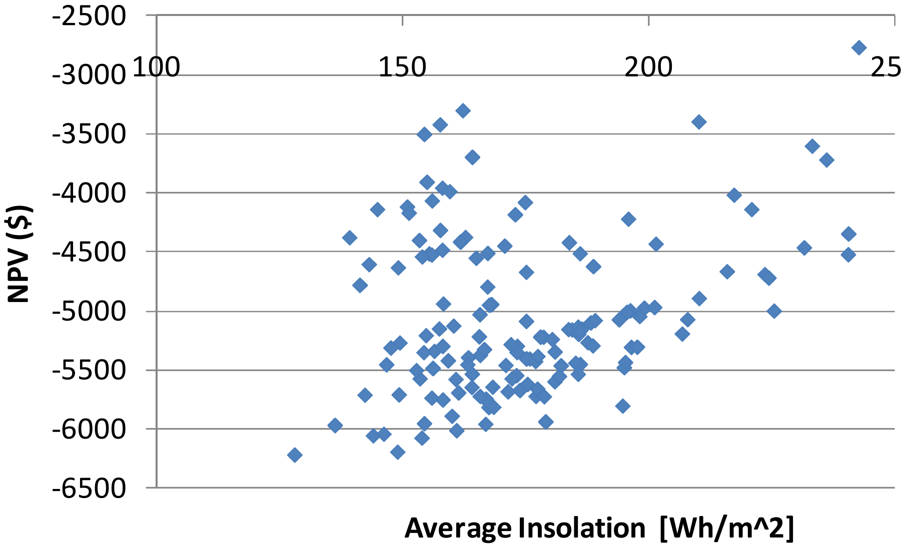


Figure 4: NPV for 2kW Residential System vs. Insolation

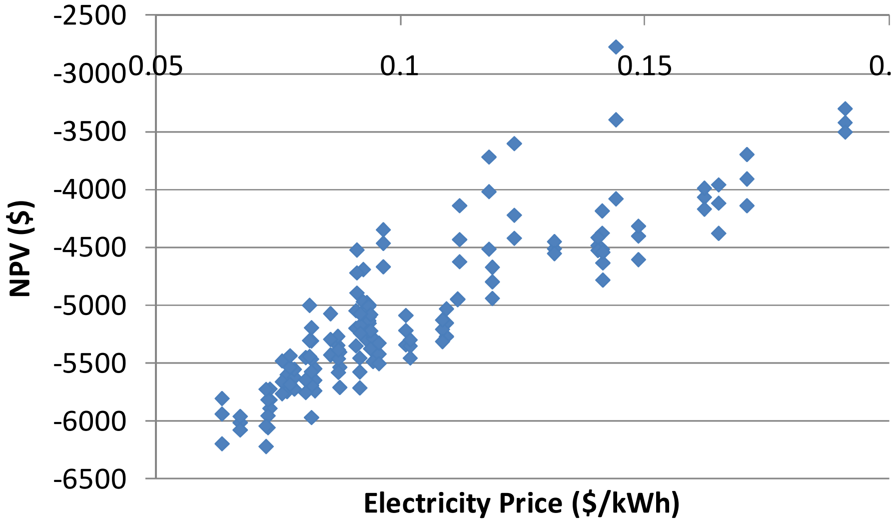


Figure 5: NPV for 2kW Residential System vs. Electricity Price

Competing with Base Load Generation

- Solar initially competes with peaking and shoulder
  - In most locations solar replaces units that operate during times with relatively high prices
  - Real-time pricing would probably raise value of solar

- To contribute significantly to energy supply solar must replace new base load generation
  - Previous analysis considered entry at zero market penetration
  - Peaking/shoulder units account for small fraction of total demand

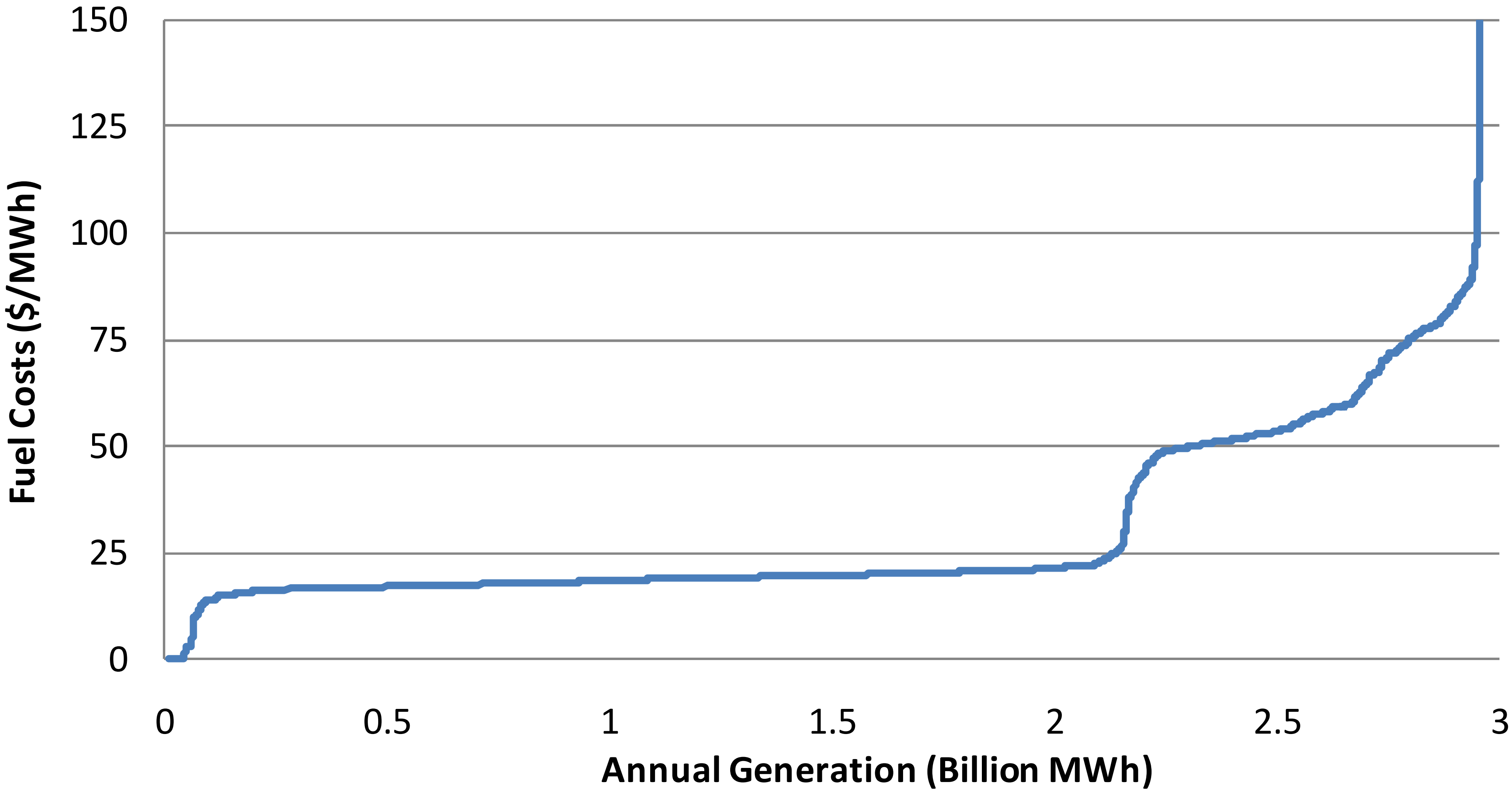
- Where do costs need to be (putting aside grid integration)?
  - Although LCOE is imperfect, it provides a reasonable comparison in the absence of grid integration concerns
  - Compare costs of solar with existing and new generating capacity
  - Assume $2.50/Wp for solar
  - Compare cost with cost of new and existing base load
  - Data from EPA (2008), EIA (2009)

Table 1

Marginal Cost, Average Cost and Generation by Technology (EIA, 2009)

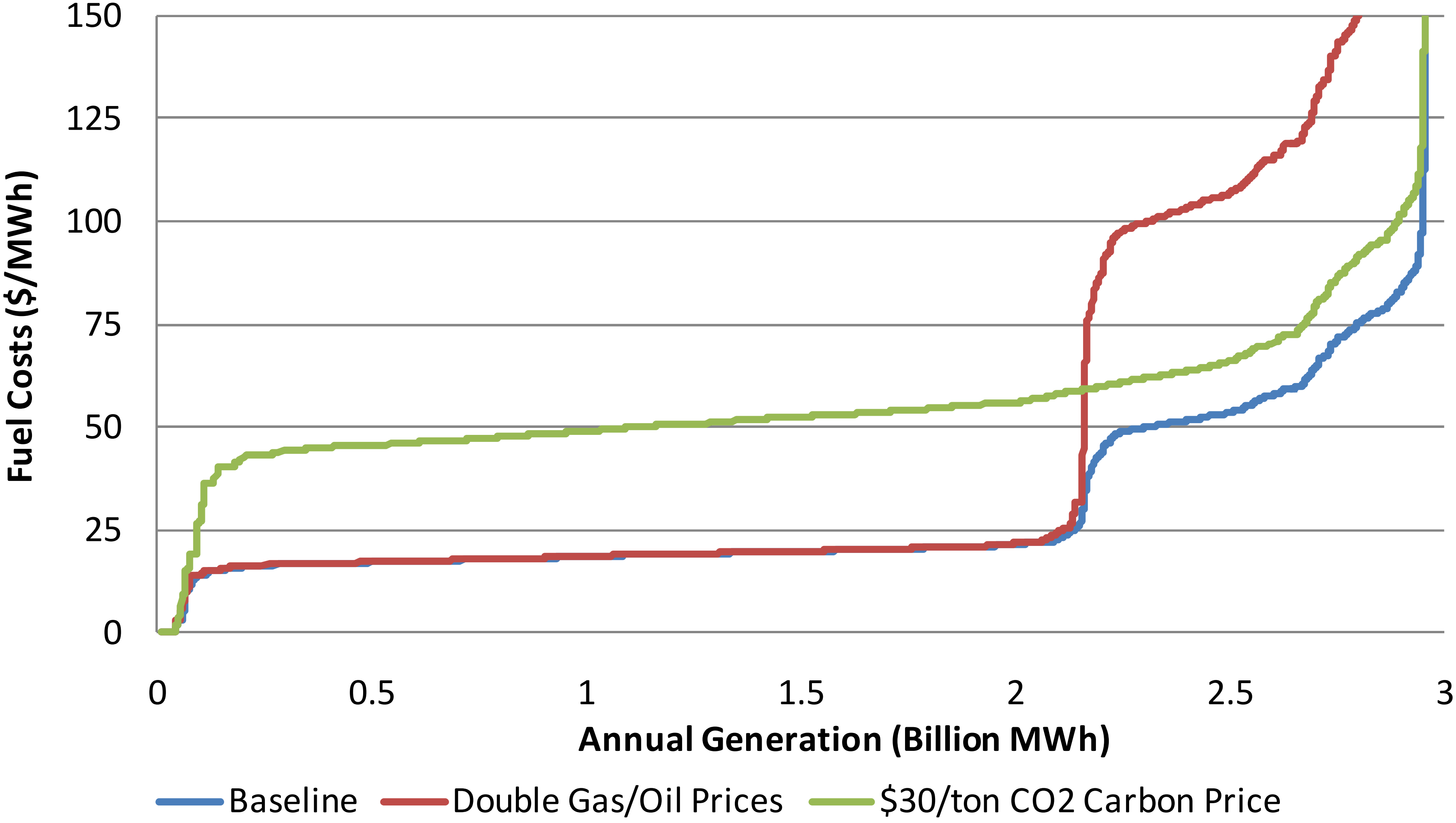
Technology	Marginal Cost ($/MWh)	Average (Levelized) Cost ($/MWh)
Conventional Coal	23.61	58.85
IGCC + CCS	26.62	86.49
Gas CC	69.74	86.21
Gas CT	105.37	197.17
Nuclear	22.33	79.16
Wind	0.00	87.82
Solar	0.00	150.68

Figure 6: Fuel Costs and Generation of Fossil Fuel Generators



Source: calculations from EPA (2008)

Figure 7: Fuel Costs and Generation of Fossil Fuel Generators



Source: calculations from EPA (2008)

Competition with Base Load (cont.)

- Conclusions:
  - Solar can almost compete with new high cost/peaking units
  - Solar is significantly more expensive than other base load technologies
  - Supply curve is steep and high cost units account for very small share of total generation

- Challenge: industry is characterized by slow turnover and low marginal costs
  - EIA forecasts 20% increase in electricity generation by 2030
  - New capacity investment of 200GW (retirements and new demand); 45% coal, ~30% gas

- Summary
  - As for any new generation technology, long-lived capital stock and low marginal costs place limits on how quickly solar can enter the market on an economic basis
  - But, a combination of factors could bring in large amounts of solar by 2050: decreasing costs, carbon price, increase in fossil fuel prices

High Penetration

- US Context
  - Some system operators have experience with wind, very few with solar
  - Preparations for solar: grid studies (e.g., 20% RPS in CA), transmission zones, etc.

- Distinguishing features of solar
  - Distributed generation
  - Variability (unexpected variation)
  - Intermittency (sun shines during the day)

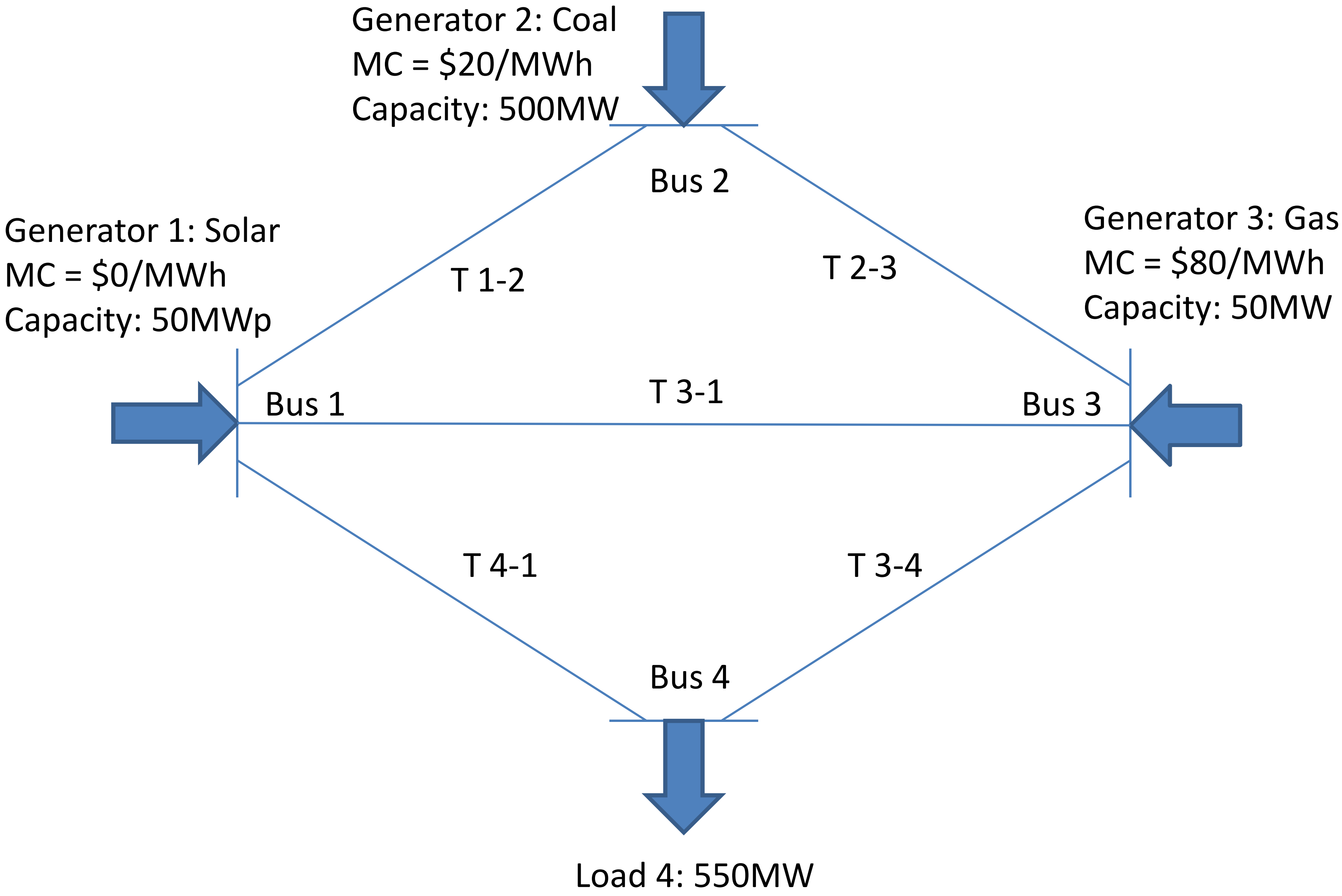
- Overview
  - Significant transmission and distribution investments are needed
  - Generation and T&D go together, so there’s more than simply connecting solar to the grid
  - Transmission issues similar to conventional technologies for utility scale, not so for distributed
  - System is designed to handle variability, but solar adds variability
  - Storage can address both variability and intermittency
  - Issues are highly system specific

Transmission and Distribution

- Two well understood issues with transmission
  - 1) Connect utility scale projects in desert to population centers
    - Grid studies assess feasibility
    - Solution: renewable energy zones
  - 2) Congestion problems arise if plant is located between existing plants and load center (e.g., wind in upstate NY)

- Less well understood:
  - Network effects
  - Connecting solar to the grid can affect dispatch of generators at other locations
  - Example: adding in 50MW of solar may require an upgrade of T 4-1 to allow coal to be dispatched from Bus 2
  - May also need to upgrade T 2-3

Figure 8: Effect of Transmission Network on Dispatch



Generator 2: Coal
MC = $20/MWh
Capacity: 500MW

Bus 2

Generator 1: Solar
MC = $0/MWh
Capacity: 50MWp

T 1-2

T 2-3

Generator 3: Gas
MC = $80/MWh
Capacity: 50MW

T 3-1

Bus 1

Bus 3

T 4-1

T 3-4

Bus 4

Load 4: 550MW

T&D (cont.)

- Distribution network: investments and connection
  - Distributed PV avoids transmission investment and congestion
  - But distribution network not designed to handle distributed generation
  - Voltage stability can be a significant concern
  - Are appropriate incentives in place for the necessary investments? Who pays for the investments? Is it easy to connect a PV system to the network?

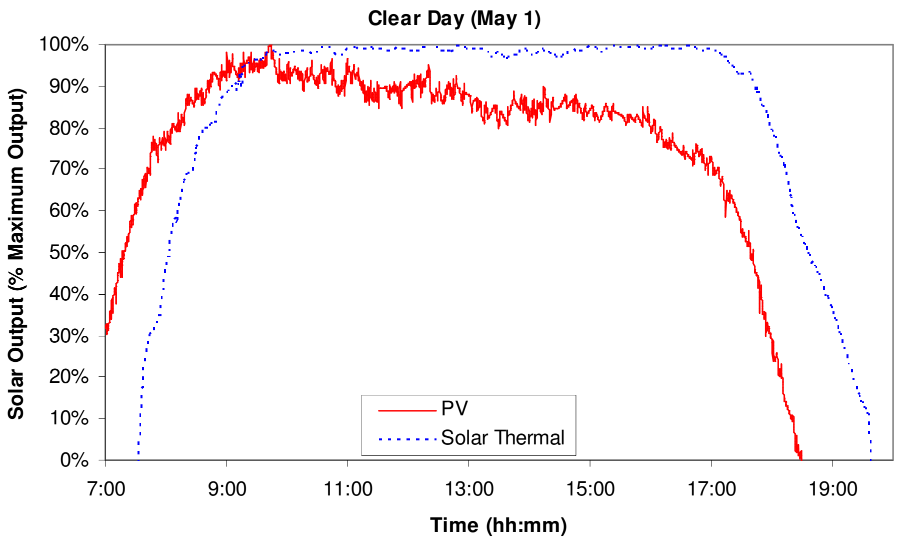
- Conclusions for transmission and distribution
  - If renewables are going to contribute significantly, policy must consider both generation and the T&D network jointly
  - Does not make sense to have a separate policies for renewables and “smart grid”
  - Furthermore, very difficult to predict loop flows, which can change suddenly due to sudden changes in output

System Operation

- Rapid fluctuations in output threaten system stability
    - Unexpected: convective clouds, aerosols
    - Expected: the sun shines during the day
    - Output can vary 40% within an hour

- Handling unexpected fluctuations
    - Inertia (~30 minutes for CSP, none for PV)
    - Forecasting and reserves 1-24 hours ahead
    - Smoothing
    - Storage

Figure 9: PV and CSP Output on a Clear and Cloudy Day



Source: U.S. DOE Report to Congress (2009)

System Operation with Unexpected Variation

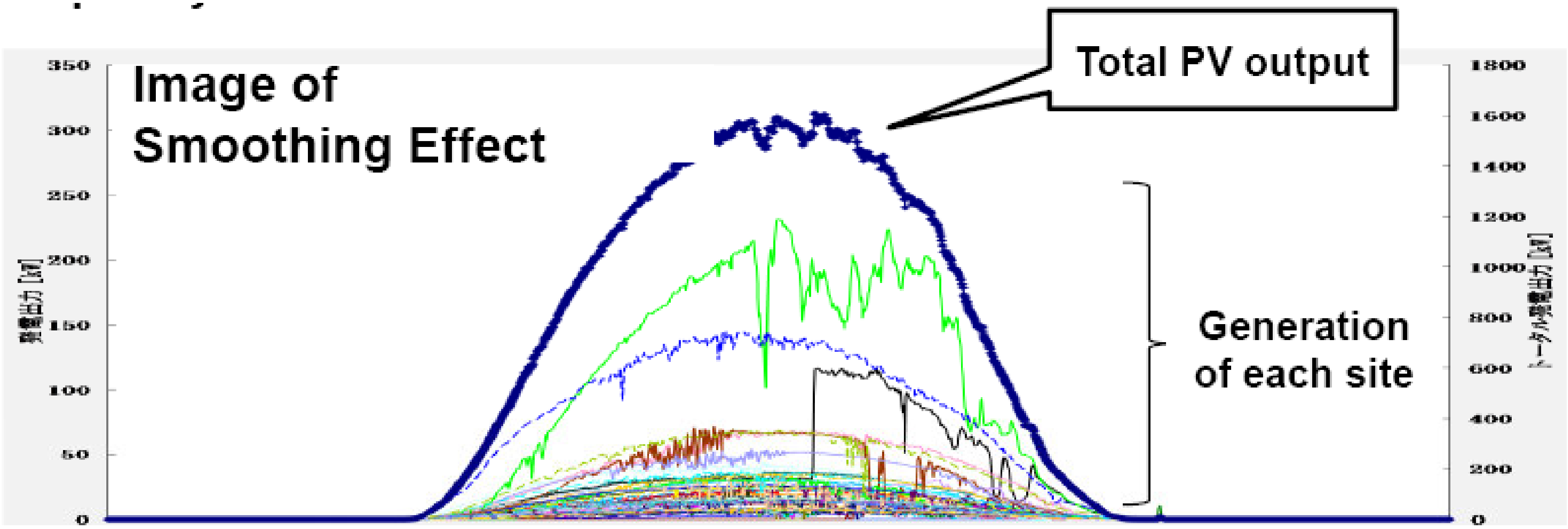
- Inertia
  - Output from CSP plant is fairly smooth
  - Output from PV is much more erratic, following atmospheric changes

- Forecasting and reserves
  - Forecast output 1-24 hours ahead and dispatch generators accordingly
  - Determine reserves in proportion to forecast error
  - Need for longer-term reserves may be significant

- Smoothing
  - Imperfect correlation in production across sites
  - Either distributed PV or connecting solar plants by transmission would smooth output
  - Correlation is higher than wind, limiting ability to smooth
  - Demand management may be better …

- Storage: small amount of storage can smooth out short-term fluctuations

Figure 10: Geographic Smoothing in Japan



Source: Ogimoto & Oozeki (2008)

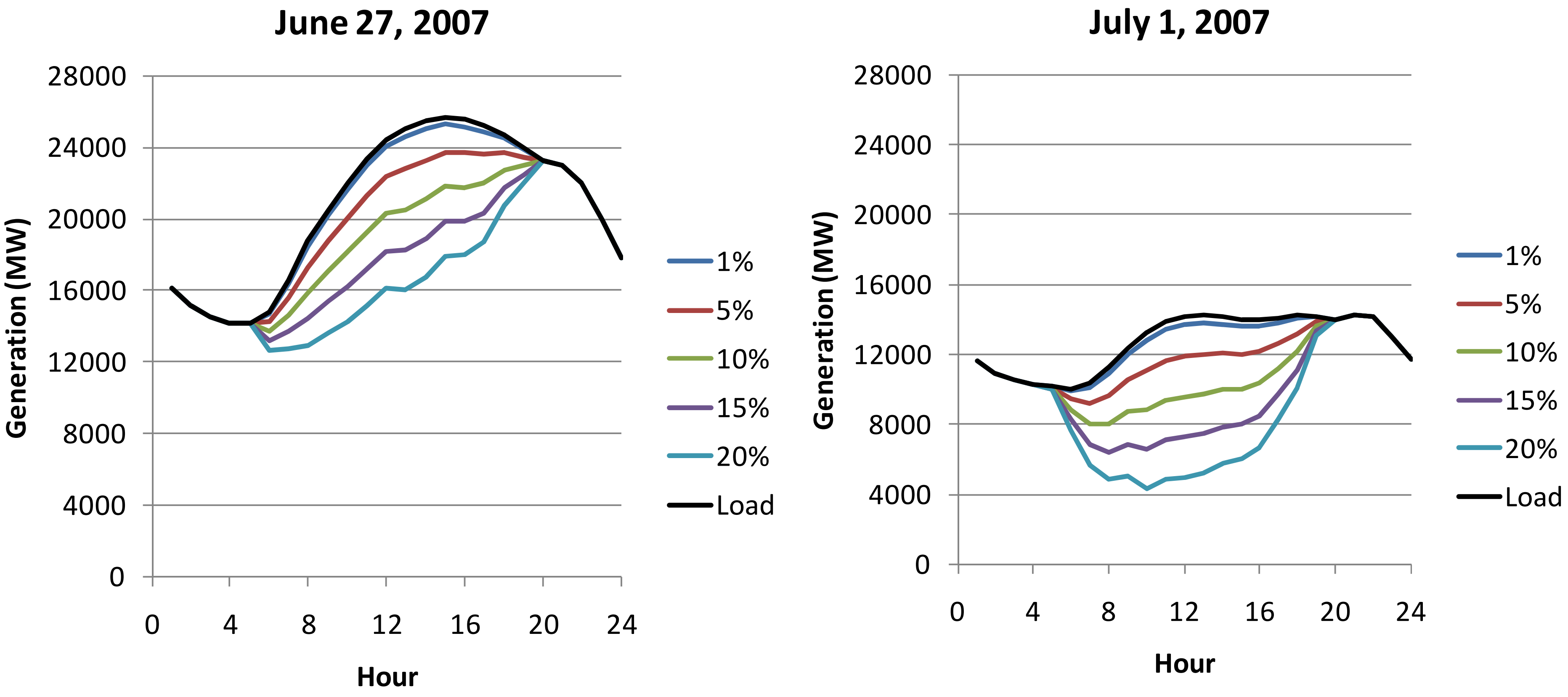
Intermittency and Dispatch

- Insolation varies over the course of a day in a predictable manner
  - Electricity production peaks mid afternoon
  - Positive correlation with electricity demand and prices

- Effect of increasing solar penetration on production from other generators
  - At low/moderate levels, solar replaces peaking and shoulder units
  - At high levels, solar would replace base load
  - Effects vary widely across systems

- Shed solar?
  - It is not always economically efficient to use all of the solar generation
  - Congestion
  - Cost of varying production from base load generators

Figure 11: Net Load and Solar Market Penetration (New England)



June 27, 2007

July 1, 2007

Source: Calculations from ISO NE and SUNY (2008)

Summary and Policy

- Challenges include costs and grid integration
  - Combination of costs, fossil fuel prices and a carbon price could make solar economically competitive
  - Solar adds variability to the system, but there are a variety of approaches to handle variability
  - Much greater premium on system flexibility, including storage
  - Integration challenges are highly system specific: network configuration, CSP vs. PV, utility vs. res./comm.

- Policies
  - Link between transmission/distribution policy and renewables policy
  - Clear, consistent, integration rules
  - System operators need to know what is being produced, particularly from distributed generation
  - Additional policies, besides a price on carbon?
    - Renewable portfolio standard
    - Investment tax credit vs. feed-in tariff
    - R&D policy