Photovoltaic Technology Experience Curves and Markets

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Outline

- History/Origins of Experience Curves
- Application to Solar PV Technology
- Thinking Prospectively Using Experience Curves
- Concluding Thoughts

Origins of the Learning Curve

- The "learning curve" describes how marginal labor cost declines with cumulative production (for a given manufactured good and firm).
  - Wright's 1936 study of airplane manufacturing found that the number of hours required to produce an airframe (an airplane body with out engines) was a decreasing function of cumulative airframes, of a particular type, produced.
  - Learning curves reflect a process of learning-by-doing or learning-by-producing *within a factory setting*.

Origins of the Experience Curve

- The "experience curve" generalizes the labor productivity learning curve to include all the cost necessary to research, develop, produce and market a given product. (Boston Consulting Group's 1968).
- Empirically the Boston Consulting Group's study found that, "costs appear to go down on value added at about 20 to 30% every time total product experience doubles for the industry as a whole, as well as for individual producers."

The General Form of the Experience Curve is the Power Curve

- $P(t) = P(0)\bullet[q(t)/q(0)]^{-b}$

  Where:

  P(t) is the average price of a product at time t

  q(t) is the cumulative production at time t

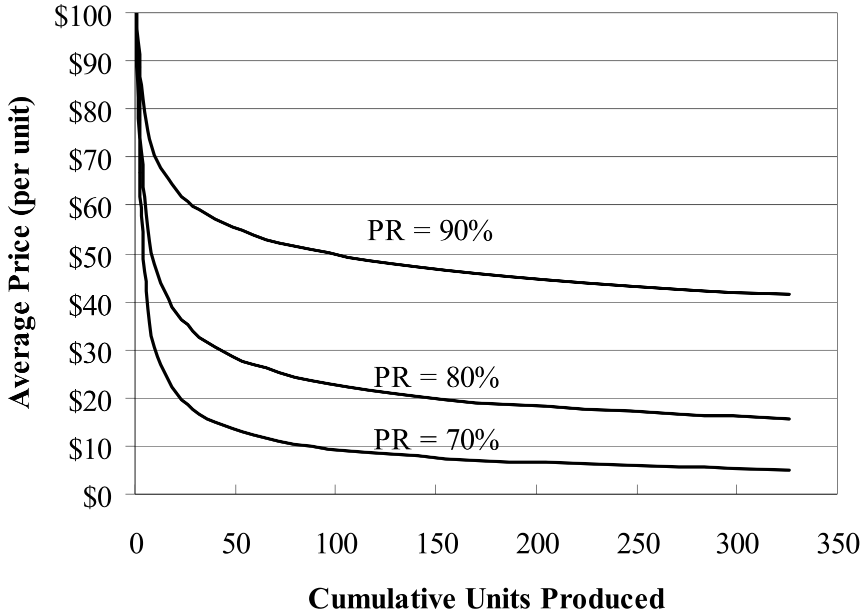
  b the learning coefficient

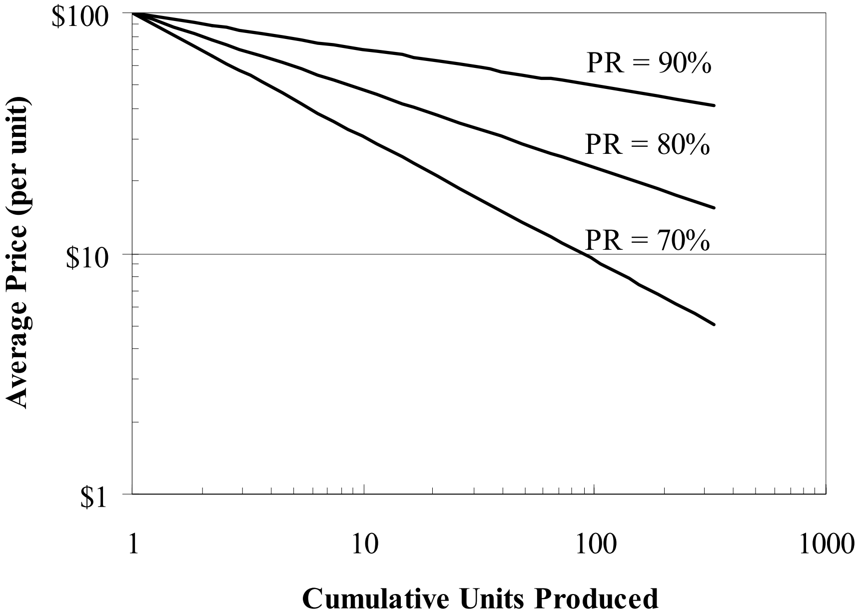
- $PR = 2^{-b}$

  Where:

  PR = progress ratio. For each doubling of cumulative production the MC decreases by (1-PR) percent.

Illustrative Learning for Three Progress Ratios





Where: P(0) = 100

q(0) = 1

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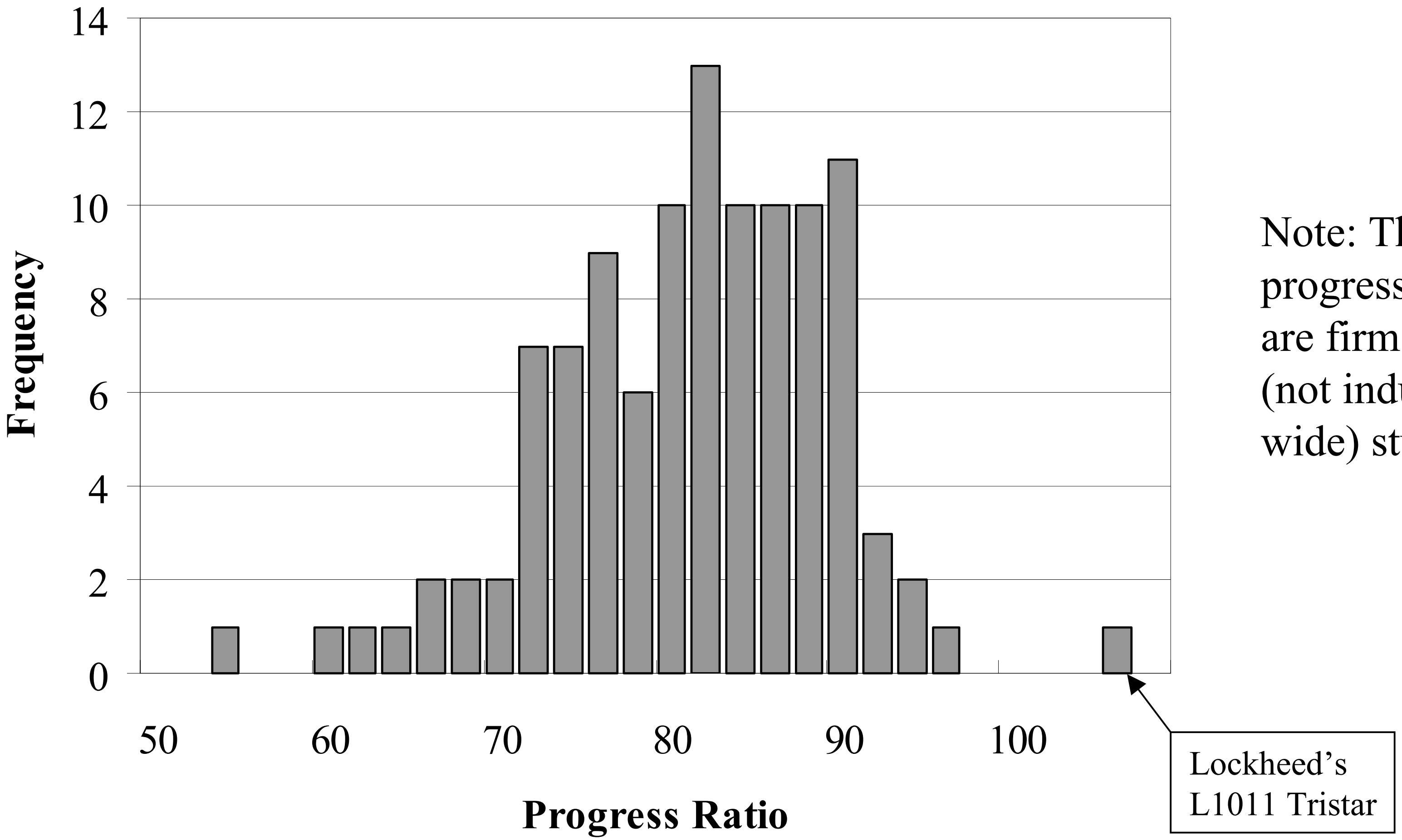
Why Might Marginal Cost of Production Decline?

- Changes in production
  - process innovations, learning effects and economies of scale.
- Changes in the product itself
  - product innovations, product redesign, and product standardization.
- Changes in input prices

➢ Experience curves typically aggregate all of these factors.

Distribution of Progress Ratios

22 Field Studies (Dutton and Thomas 1984)



Note: These progress ratios are firm level (not industry wide) studies.

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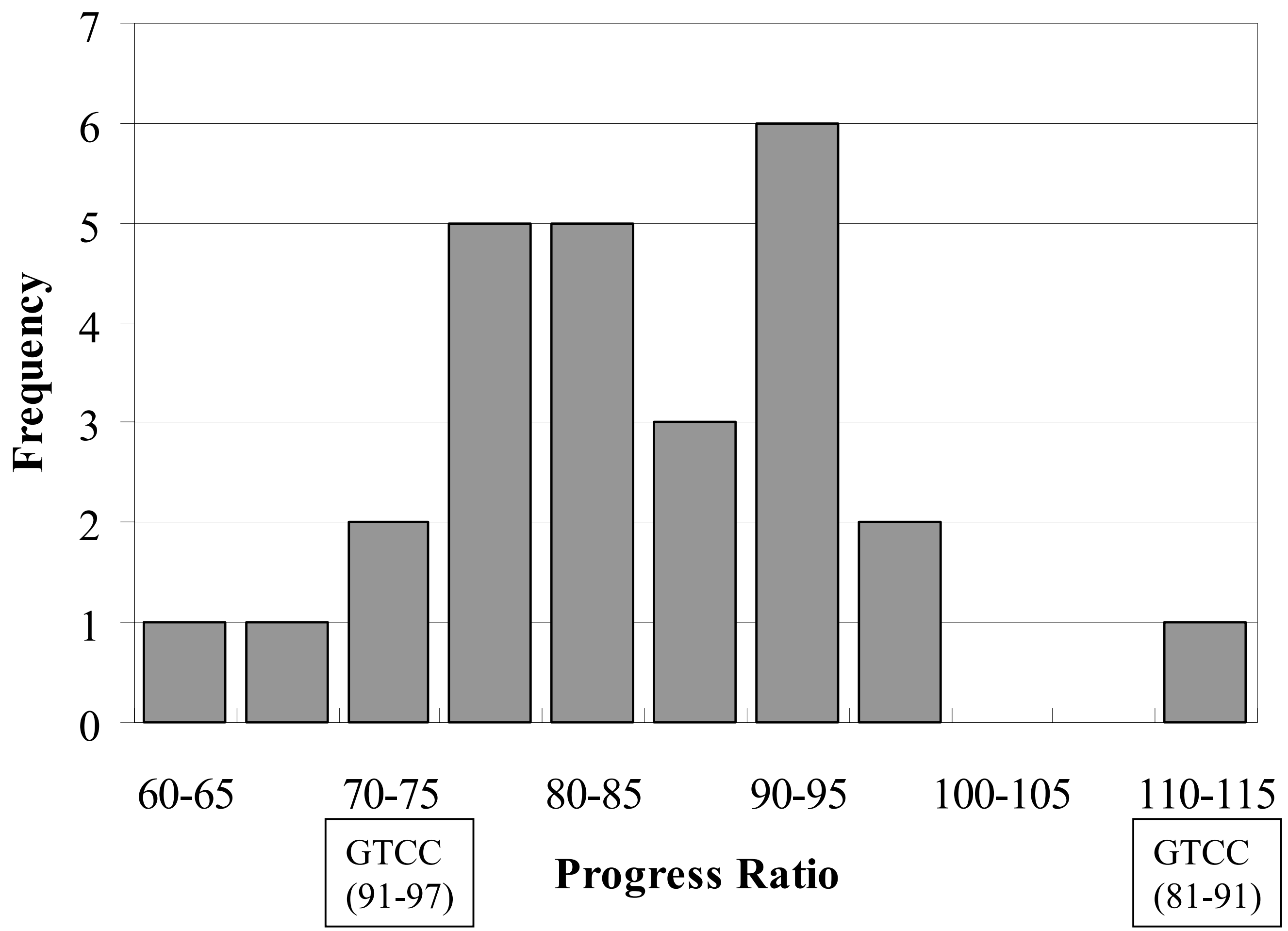
Distribution of Energy Progress Ratios
(McDonald and Schrattenholzer 2001)



Note: Includes a wide range of Energy technologies: oil extraction, power conversion, model T Ford, CF lights, etc.

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PV Progress Ratios from Selected Studies

Study	**PR**	**# of obs**	**Years**	**Scope**	**Cost/Price Measure**
Maycock & Wakefield (1975)	78%	16	1959-1974	US	PV Module Sale Price
Williams & Terzian (1993)	82%	17	1976-1992	Global	Factory Module Price
Cody & Tiedje (1997)	78%	13	1976-1988	Global	Factory Module Price
Williams (1998)	82%	19	1976-1994	Global	PV Module Price
Maycock (1998)	68%	18	1979-1996	Global	PV Module Price
Tsuchiya (1999)	84%	20	1979-1998	Japan	PV Module Gov't Purchase Price
Harmon (2000)	80%	21	1968-1998	Global	PV Module
IEA (2000)	65%	11	1985-1995	EU	PV System Electricity Cost (ECU/kWh)
IEA (2000)	84% 53% 79%	9 4 10	1976-1984 1984-1987 1987-1996	EU	PV Module Price

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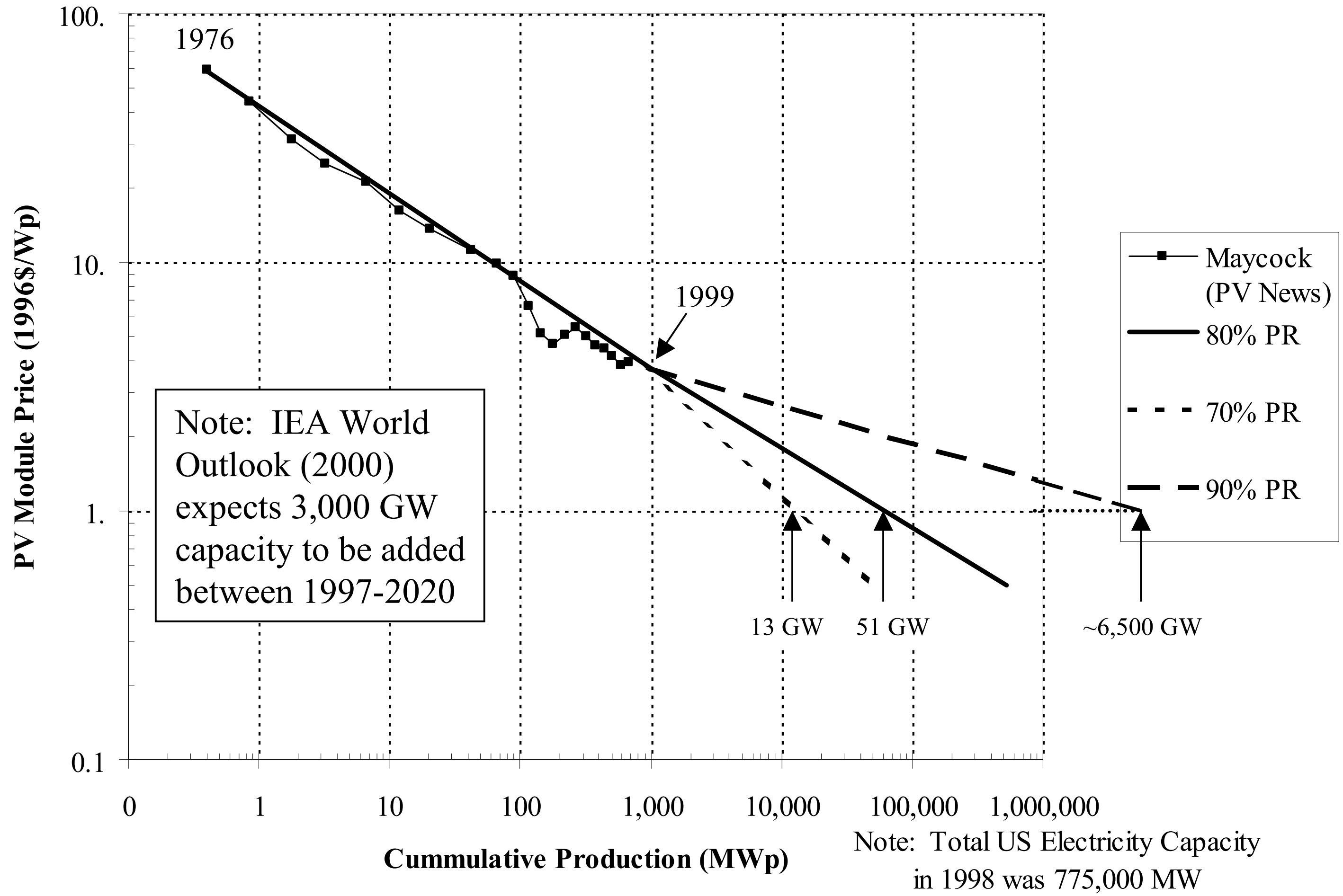
A Typical Learning Based Projection for PV



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PV "Buy-down" Cost from Selected Studies

Study	Time Period	Target Level	Estimated Buy-Down Cost	Notes
Neij (1997)	1995-various	$0.05 /kWh	$100 billion (0.8 PR) $20 billion (0.7 PR)	Subsidize all future purchases above target cost. Total system cost.
Wene (1999)	1997-not specified	$0.5/Wp	$60 billion	Subsidize all future purchases above target cost. PV module only.
Wene (1999)	1998-2007	$3/Wp	$1.2 billion	Japanese government investment. Total system cost.
Williams (1998)	1997-2006	$1000 /kW	$50 billion (x-Si targeted) $120 million (a-Si targeted)	Subsidize all future purchases above target cost. PV module only.
Williams and Terzian (1993)	1995-2020	$1100 /kW	$5.4 billion (Net benefits accounting for environmental externalities)	Subsidize only additional purchases relative to baseline. Total system cost.

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Thinking Prospectively

- Five key factors help to explain the wide variation in PV buy-down costs estimates:
  - Choosing an appropriate target level
  - Focusing on the module vs. system costs
  - Calculating program costs relative to a baseline
  - Using a single vs. a range of progress ratios
  - The availability of breakthrough technologies

What's the Right Target Level?

- Depends on targeted application
  - Rooftop/BIPV: Retail Electricity Rate
  - Large-Scale Power: Wholesale Rate
  - Telecom: Currently competitive in many remote locations
  - Solar Home Systems: Economically viable when remote from the grid

➢ Recalculating Neij's estimate with alternative targets:

Target Level (~ retail rate in)	**Subsidy Required to Meet Target**	
	PR = 0.8	**PR = 0.7**
$0.05/kWh (Neij)	$100 billion	$20 billion
$0.085/kWh (U.S.)	$32 billion	$9 billion
$0.16/kWh (Germany)	$6 billion	$2 billion
$0.21/kWh (Japan)	$2 billion	$1 billion

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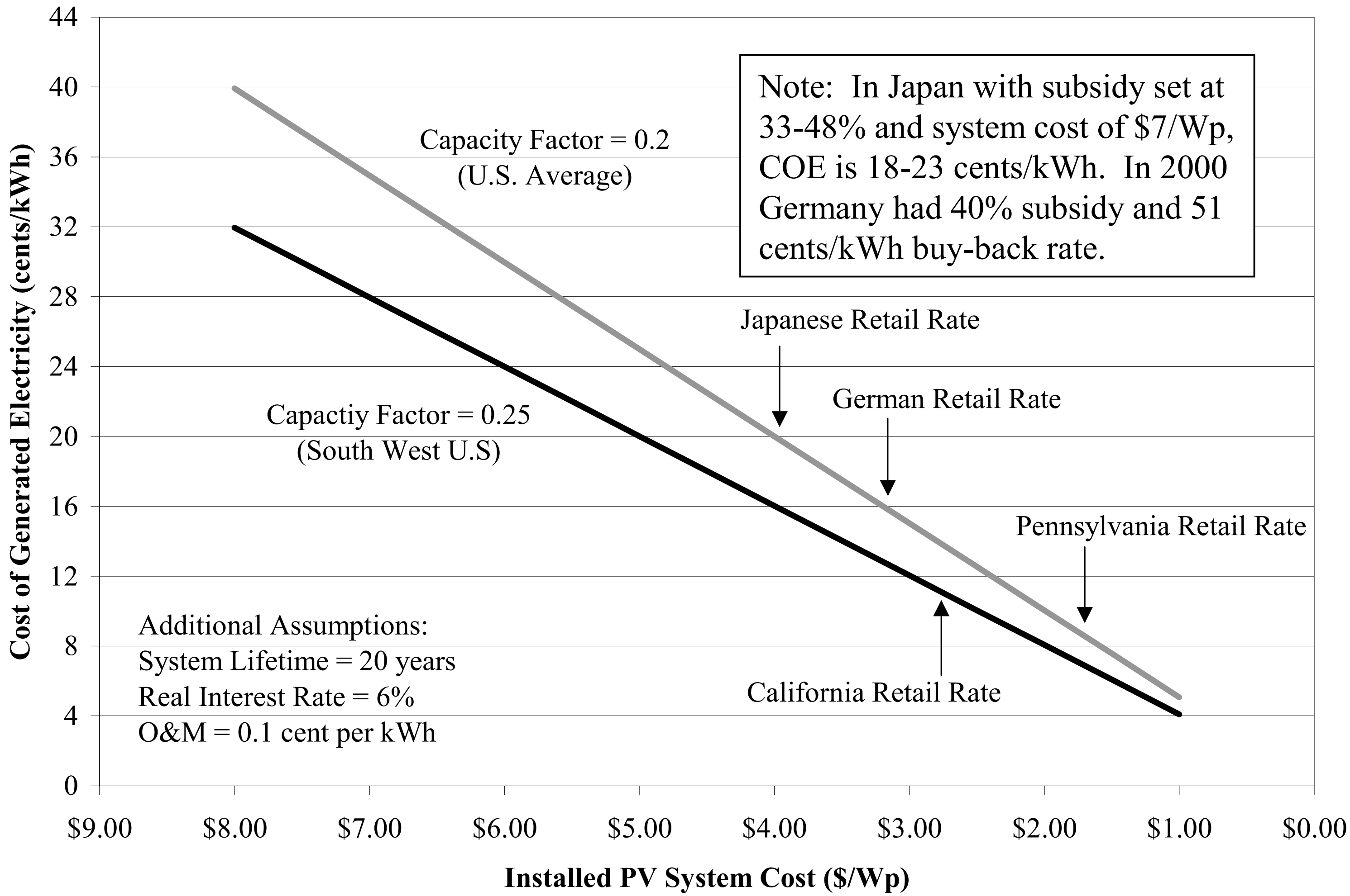
PV System vs. Electricity Costs



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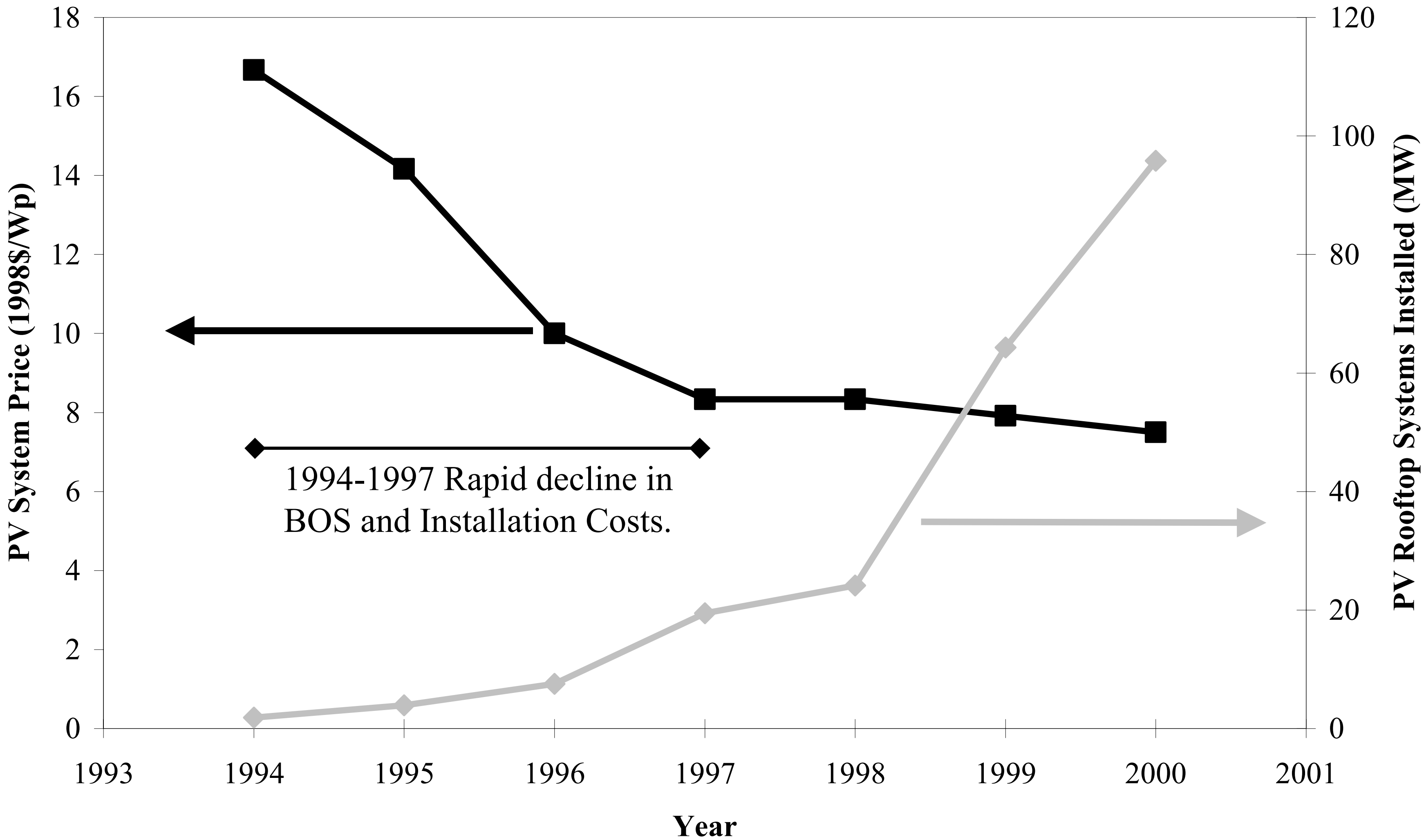
Module vs Systems Costs

- Really a compound learning curve
  - PV module
  - Balance of System components
    - Rooftop/BIPV offers many opportunities for cost reduction
      - Elimination of Storage
      - Substitute structurally
      - Elimination of frame
  - Installation
- Different components may have different learning rates.

Japanese Rooftop Program Experience, 1994-2000



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Impacts Relative to a Baseline

- PV has niche markets that are likely to grow
- Can target subsidies (as in Japan and Germany)
- A simple illustration:
  - PR = 0.8, System Cost in 1998 = $7/Wp
    - ➢ To achieve $3/Wp target by 2009 (i.e., 30% growth)

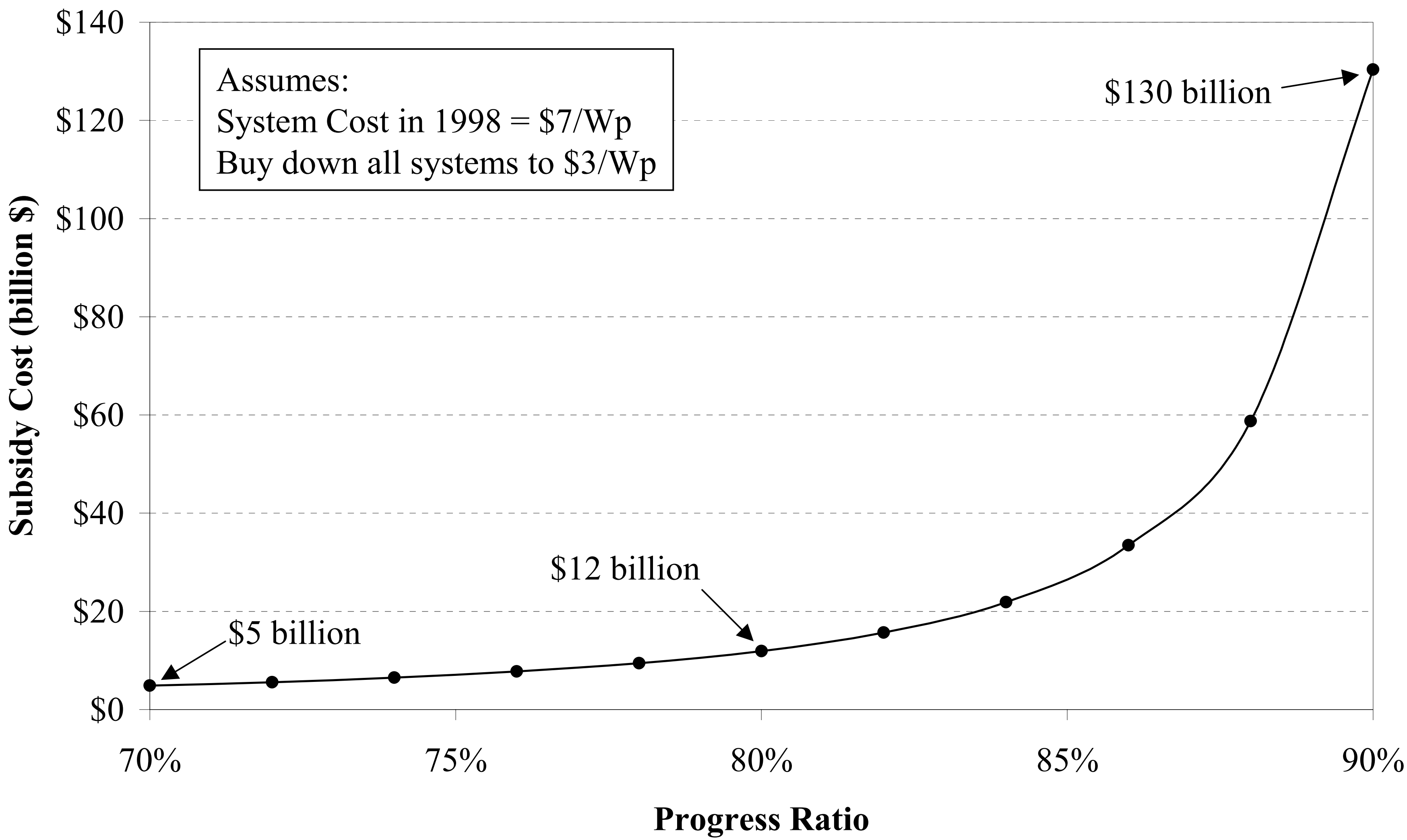
Baseline Growth Rate	**Subsidy Required to Achieve $3/Wp Target by 2009**
0%	$11 billion
10%	$6 billion
20%	$4 billion

Using a Single Progress Ratio?

- There is considerable uncertainty in historical progress ratios
  - What is the relationship between R&D and progress ratios?
- Results are highly sensitive to progress ratio

➢ Need to include sensitivity analysis.

Sensitivity of Global PV System Subsidy Cost to PR



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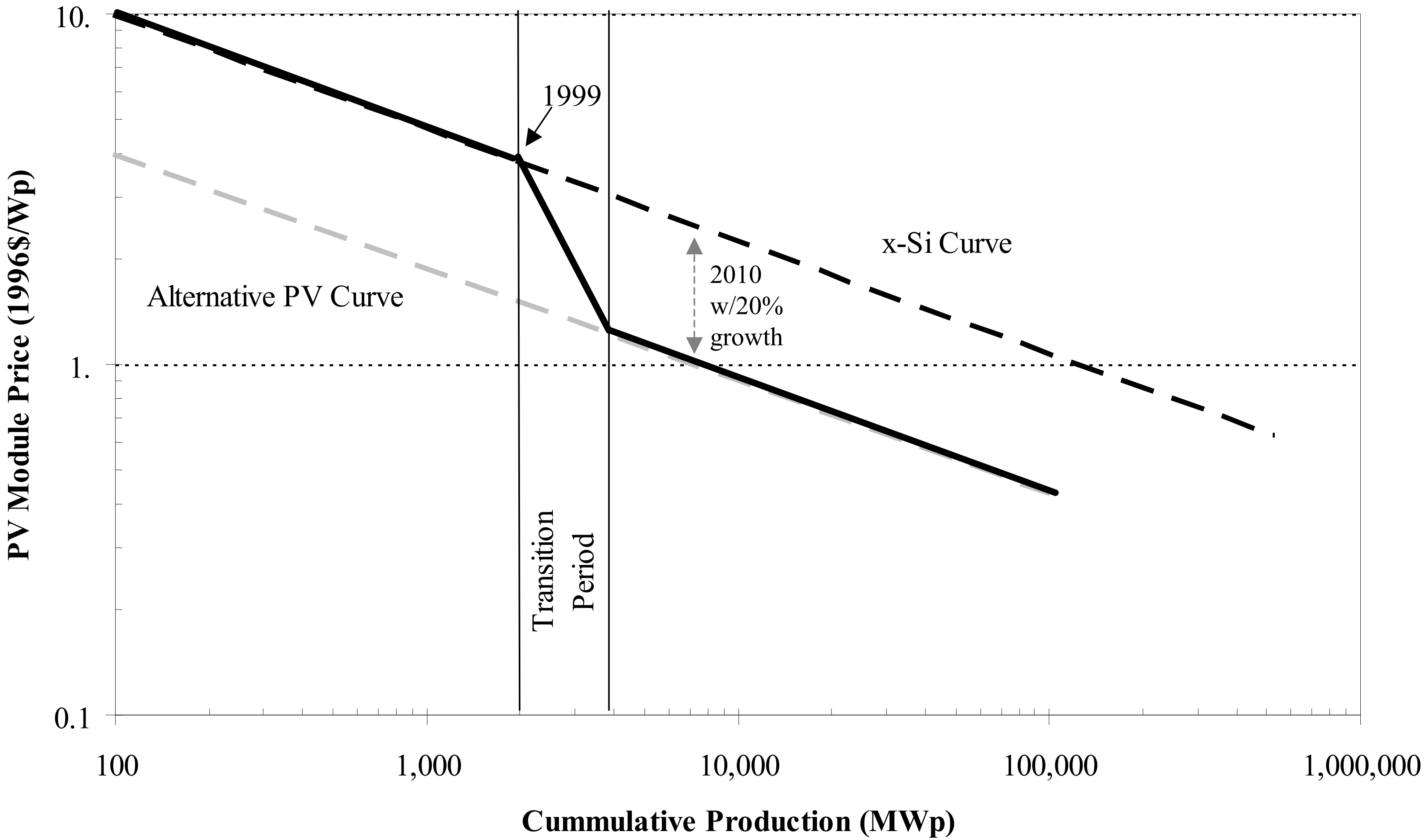
Assumptions about Breakthroughs

- The potential for breakthroughs is difficult to quantify
- Little basis for drawing experience curves for emerging PV technologies

➢ Yet, breakthroughs could have dramatic impact on PV technology development path.

Illustrating a Breakthrough in PV Technology



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Concluding Thoughts

- Process of innovation is inherently uncertain
  - prospects for future learning with existing technologies
  - breakthroughs (i.e., through R&D investments)
  - market developments (i.e., how rapidly the grid-connected and rural home markets will grow).
- ➢ Need to be cautious!
  - Simplistic use of industry-wide experience curves can easily mask the underlying dynamics of the process of innovation.

Concluding Thoughts (cont.)

- With respect to PV technology we are in what Cowan (2000) calls the "narrow windows" and "blind giants" stage of technology development.*
  - There is a wide range of emerging PV technologies.
  - It is currently unclear which PV technology will dominate the market in the long-run.
  - ➢ Government should encourage the development and diffusion of a diverse set of PV technologies.

* That is, effective policy-making is only possible during the early stages of competition between technologies, yet that is when analysts and policy-makers know the least about what to do.