Challenges to the adoption and large-scale integration of emergent energy technologies

MAE 119 Lecture
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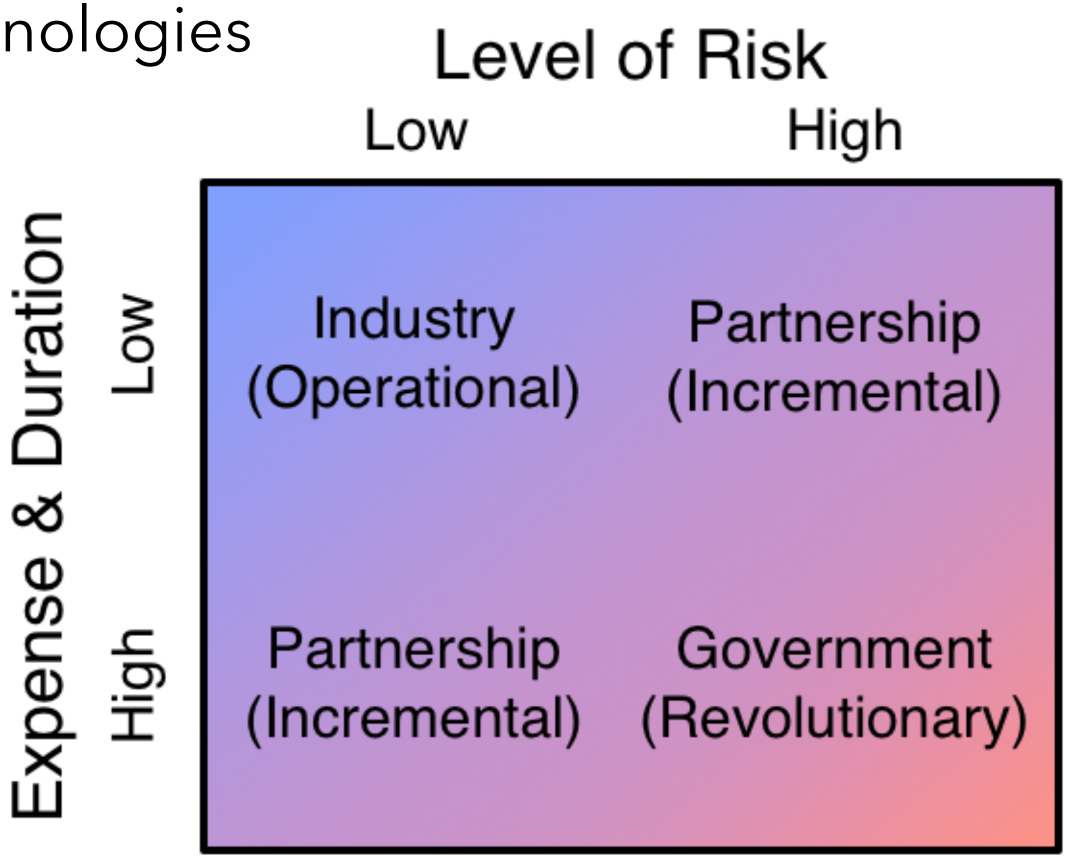
The role of government support

- Varied takes on the role of government in supporting emergent energy technologies
  - Establish coherent industrial policy (China, Japan)
  - Get out of the business entirely



Abdulla, Ford, Morgan, Victor (2017) *ERL*

What happens when you leave the lab?

- Your technology will likely be economically uncompetitive
- You can improve its commercial viability by exploiting either learning economies or economies of scale (or both):

Learning economies:
Products cost less, and activities take less time, the more you deploy or repeat them

Economies of scale:
The larger your equipment is, the smaller the cost per unit output (process being equal)

The history of learning curves

- First applied in industry by T.P. Wright in 1936: “Factors affecting the cost of airplanes”
- RAND, then Arrow (1963)

> “The attitude outside the industry is usually quite supercilious with the intimation present that everyone engaged in the design, development, or construction of airplanes is a sort of prima donna.”

FEBRUARY, 1936 JOURNAL OF THE AERONAUTICAL SCIENCES VOLUME 3

Factors Affecting the Cost of Airplanes

Presented at the Aircraft Operations Session, Fourth Annual Meeting, I. Ae. S.
T. P. Wright, *Curtiss-Wright Corporation*

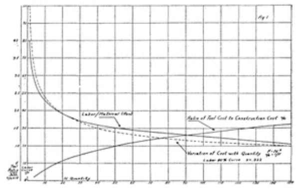
Introduction

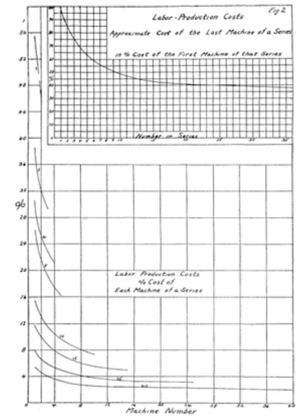
THIS subject is one which can always be relied upon to start a discussion whenever it is raised in aircraft circles. Great differences of opinion will be voiced as to the relative importance of various factors, depending somewhat on whether the discussion is between persons in the industry who are engaged in sales, engineering, design or factory work. The attitude of those outside the industry is usually quite supercilious with the intimation present that everyone engaged in the design, development, or construction of airplanes is a sort of prima donna. Therefore, because of the rather hazy information which seems to surround the subject, it appears in order to discuss the problems from several points of view in an effort to arrive at logical conclusions.

The effect of quantity production on cost, particularly, requires study as in this respect more than in others, there exists a lack of appreciation of the variation which occurs. Recently the matter became of increasing interest and importance because of the program sponsored by the Bureau of Air Commerce for the development of a small two-place airplane which, it was hoped, could be marketed at $700 assuming a quantity of ten thousand units could be released for construction.

The present writer started his studies of the variation of cost with quantity in 1922. A curve depicting such variation was worked up empirically from the two or three points which previous production experience of the same model in differing quantities made possible. Through the succeeding years, this original curve, which at first showed the variation in labor only, was used for estimating purposes and was corrected as more data became available. The form which this curve takes when plotted on plain cross-section paper is shown in Fig. 1. On this figure there is also shown the variation of the ratio of labor to raw material as quantity varies. The correcting of curves of this type by new points of actual experience resulted in data which permitted other curves to be plotted, showing the variation of raw material, purchased material, and finally, of the whole airplane, against quantity.

Effort was also made to plot the cost of each machine of a series in percent of the total cost of the series for varying quantities. The work along this line is shown in Fig. 2 which, however, must be considered as more approximate in accuracy than the others because of the greater difficulty in securing reliable empirical information on the relative cost of each machine of a series, since accounting methods seldom reveal such data. However, the curves of Fig. 2 are believed to show the general shape of curves and trend of data of this kind.

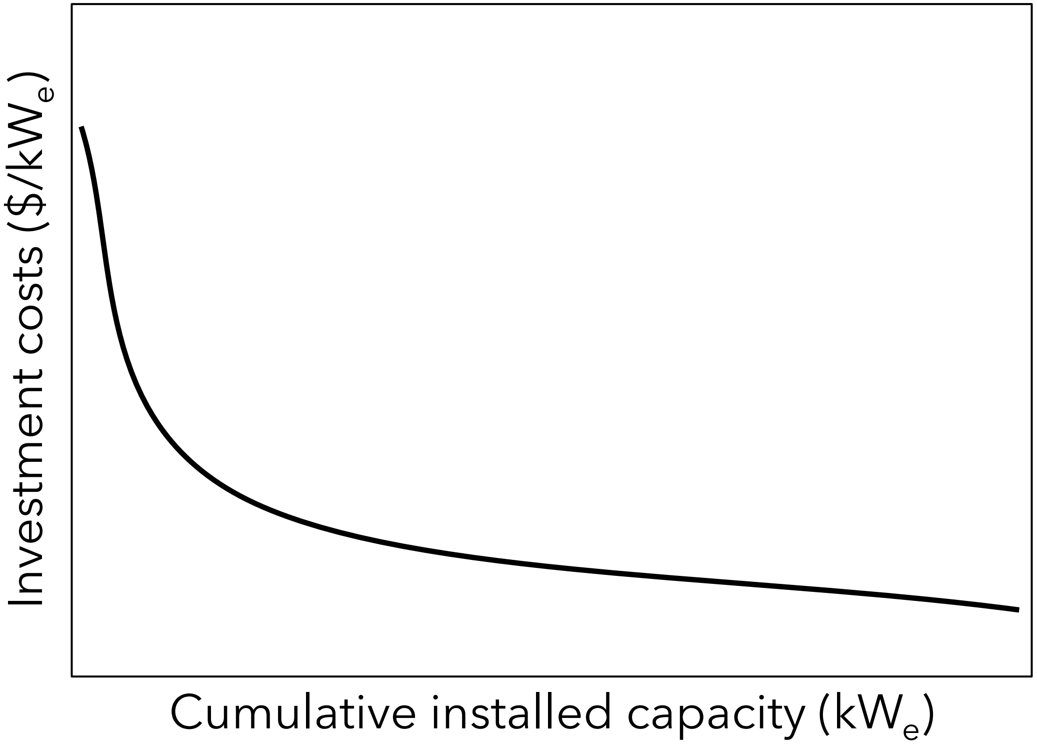




Wright TP (1936) Factors affecting the cost of airplanes” Journal of the Aeronautical Sciences 3(4):122-128

Learning (or experience) curves

- Theory based on a doubling of production. If you double the number of products built, or cumulative capacity of a technology installed, the cost goes down by x%



The classic one-factor experience curve

$$C_i = a\, x_i^{-b}$$

where	C_i	is	the cost to produce the i^{th} unit
	a	is	a coefficient
	x_i	is	the cumulative installed capacity through period i
	b	is	the learning rate exponent

The learning rate (LR) is the cost reduction that occurs after each doubling of installed capacity. It is defined as:

$$LR = 1 - 2^b$$

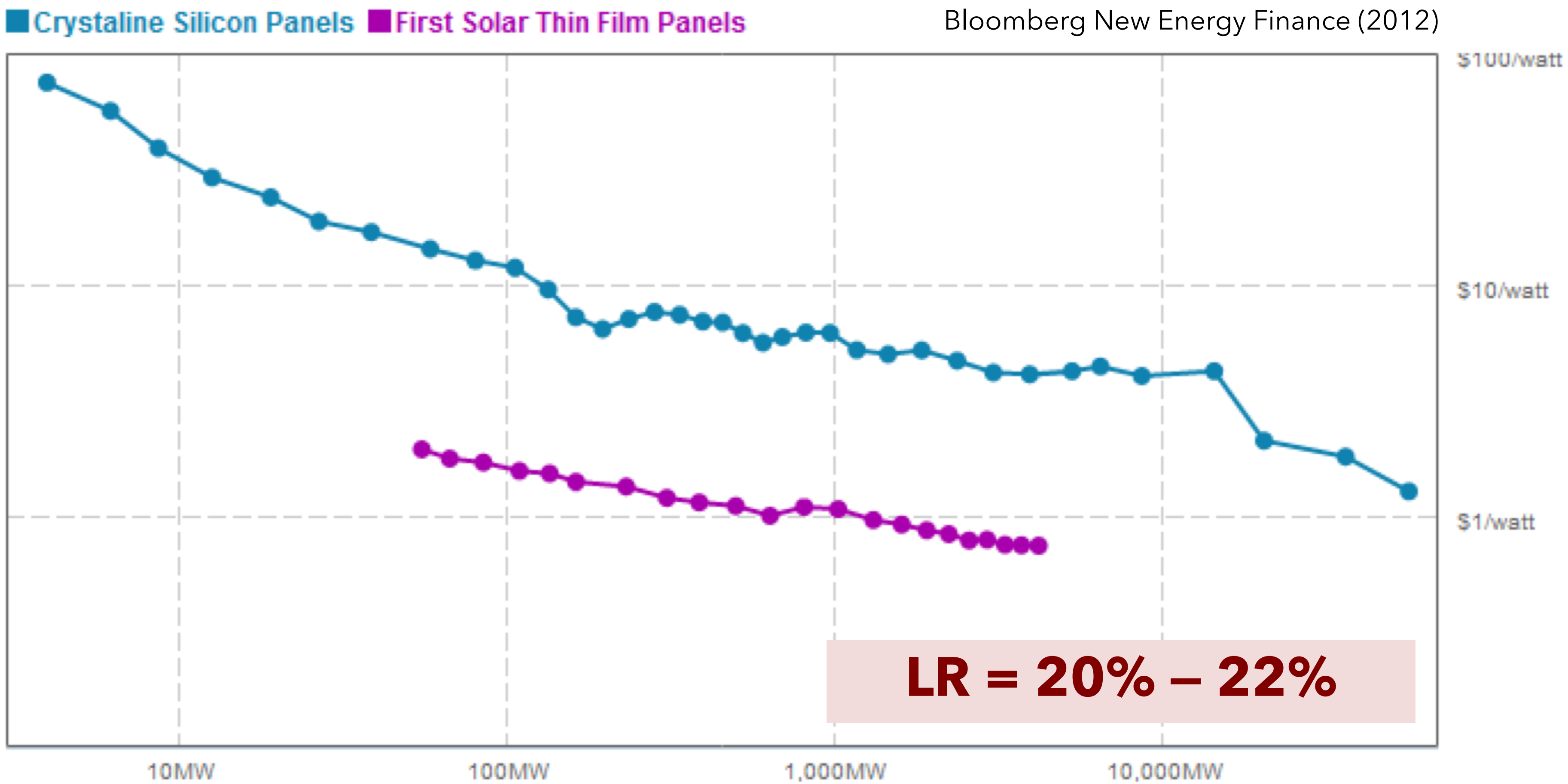
Application to wide range of industries

Example	Improving Parameter	Cumulative Parameter	Learning-Curve Slope (%)
1. Model-T Ford production	Price	Units produced	86
2. Aircraft assembly	Direct labor-hours per unit	Units produced	80
3. Equipment maintenance at GE	Average time to replace a group of parts	Number of replacements	76
4. Steel production	Production worker labor-hours per unit produced	Units produced	79
5. Integrated circuits	Average price per unit	Units produced	72[a]
6. Hand-held calculator	Average factory selling price	Units produced	74
7. Disk memory drives	Average price per bit	Number of bits	76
8. Heart transplants	1-year death rates	Transplants completed	79

[a]Constant dollars.

Module E: Learning Curves in Heizer J, Render B, Munson C (2017) Operations Management: Sustainability and Supply Chain Management, 12th Edition (Pearson)

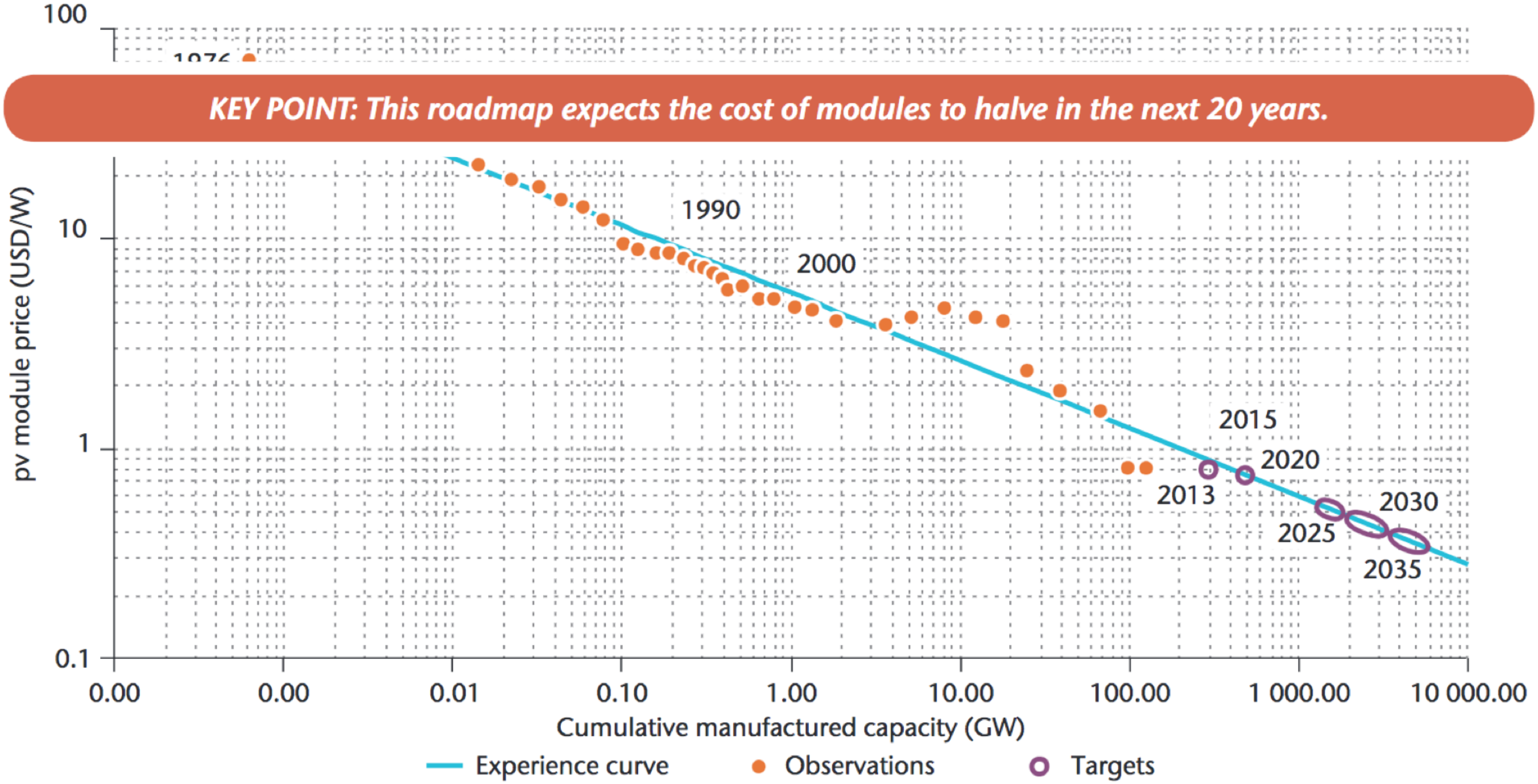
① Solar PV learning curve



① Solar PV learning curve

Figure 10: Past modules prices and projection to 2035 based on learning curve

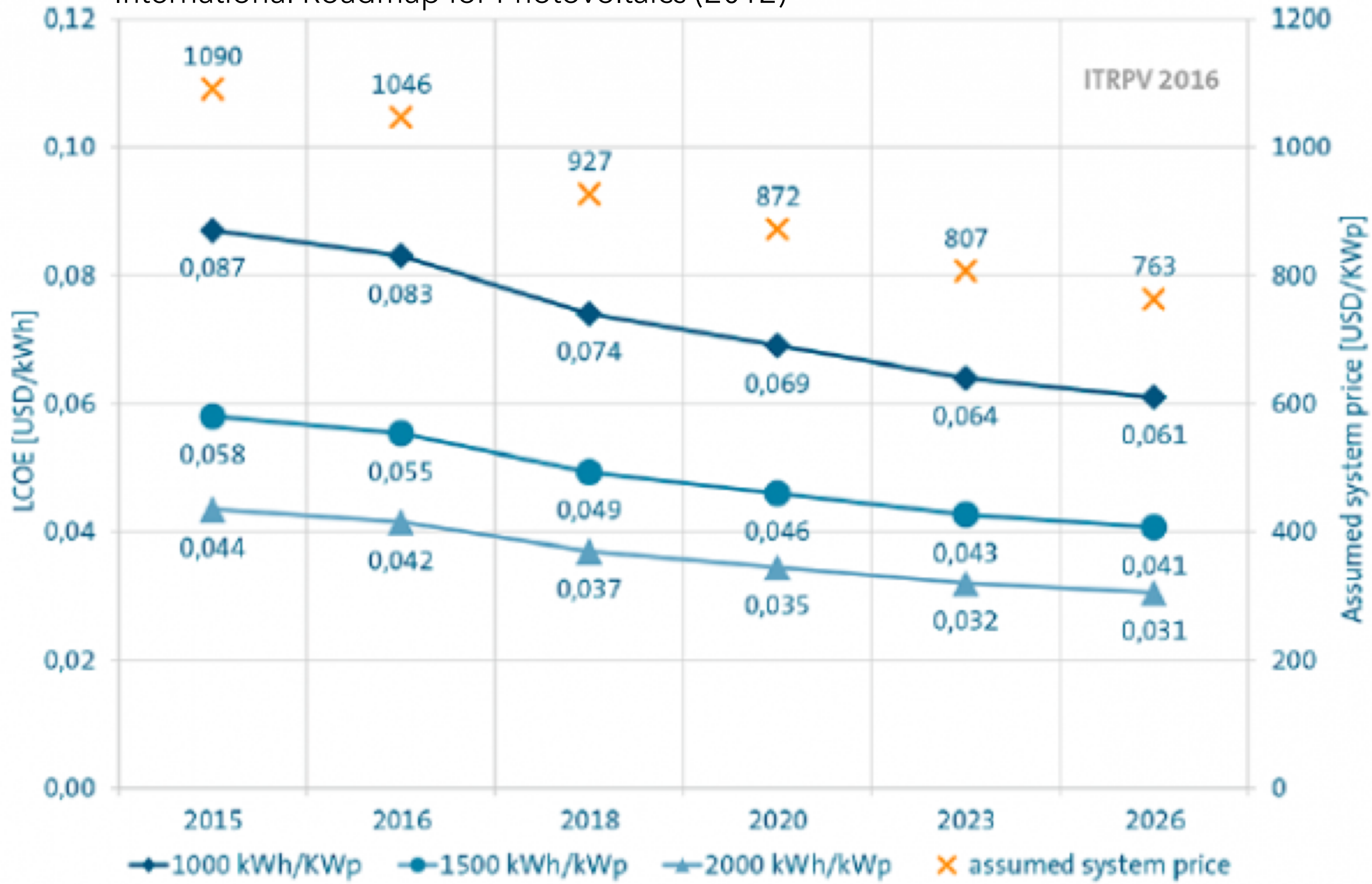
Technology Roadmap: Solar Photovoltaic Energy (2014) International Energy Agency



KEY POINT: This roadmap expects the cost of modules to halve in the next 20 years.

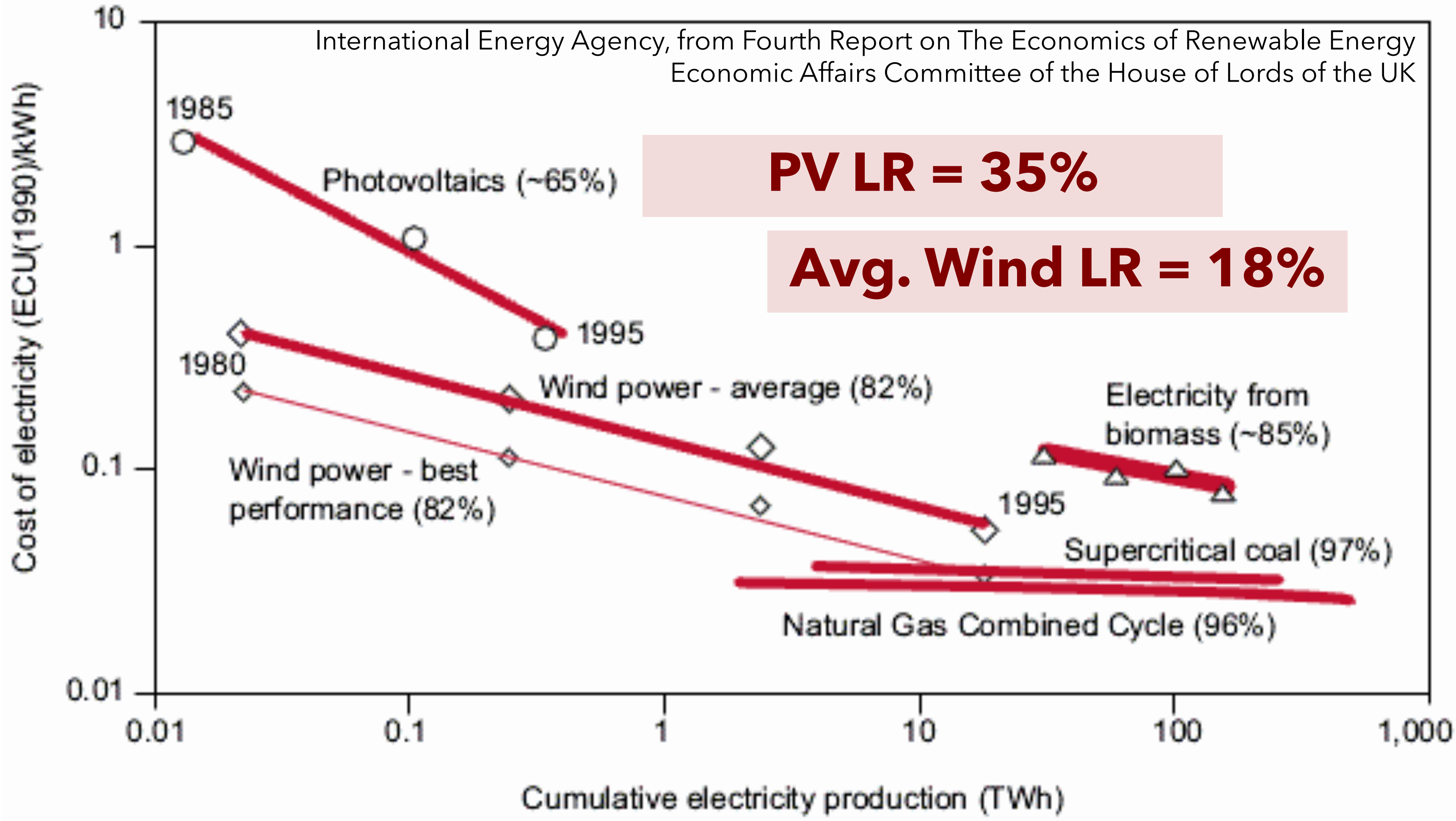
① Solar PV learning curve

International Roadmap for Photovoltaics (2012)



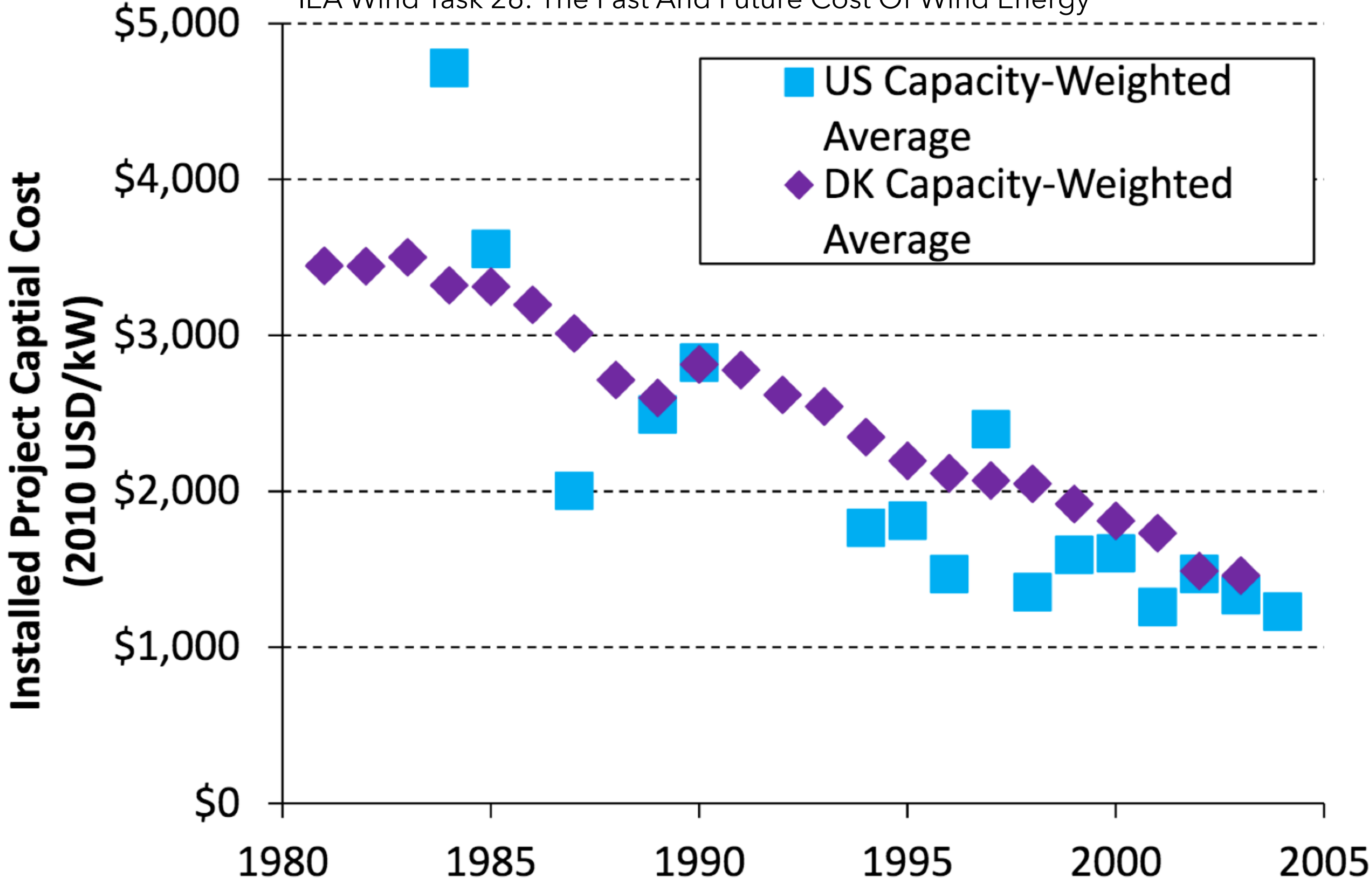
Calculated LCOE values for different insolation conditions. Financial conditions: 80% debt, 5%/a interest rate, 20-year loan tenor, 2%/a inflation rate, 25 years usable system service life.

② Wind power's learning curve



② Wind power's learning curve

National Renewable Energy Laboratory (2012)
IEA Wind Task 26: The Past And Future Cost Of Wind Energy



② Wind power's learning curve

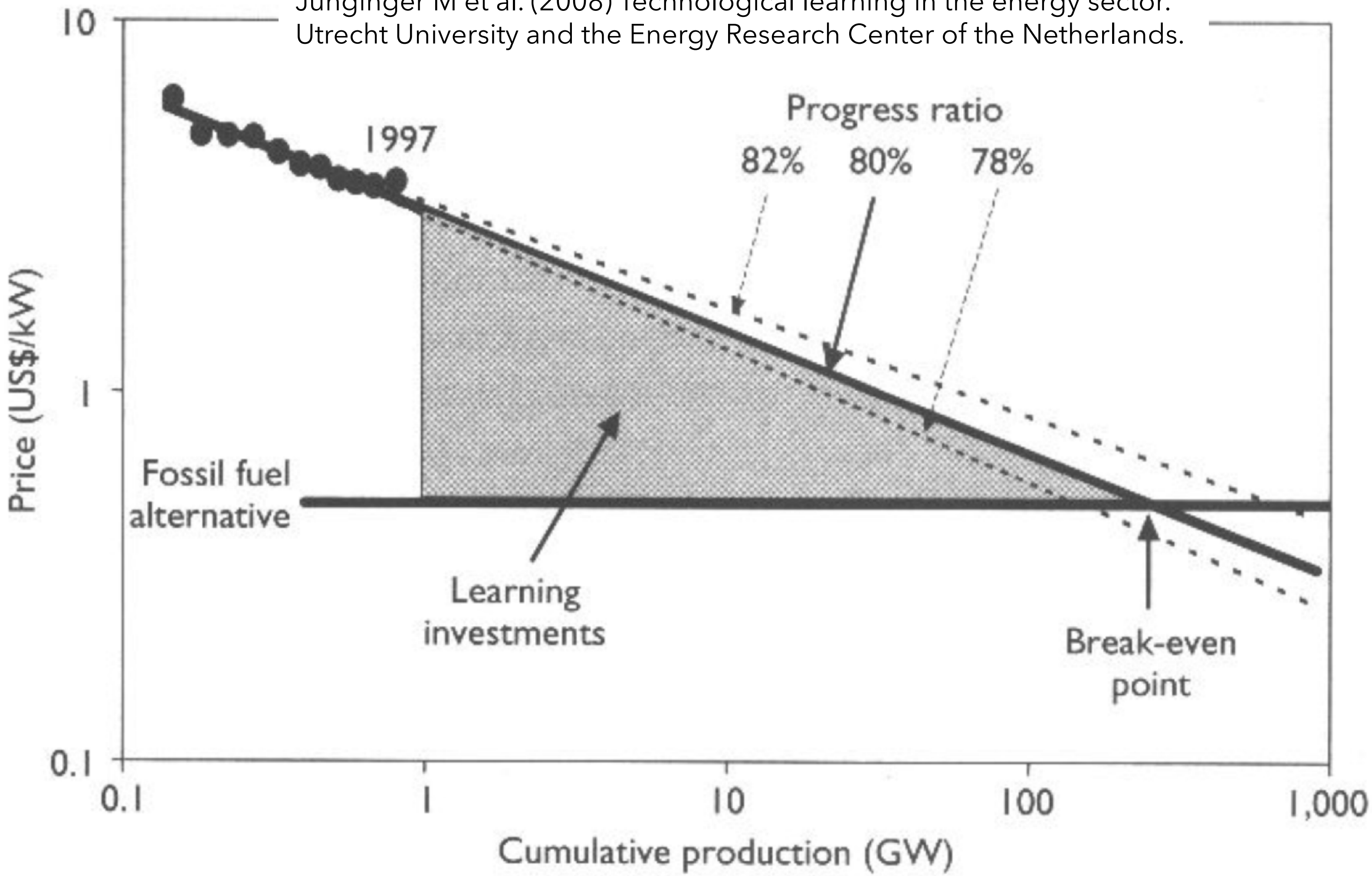
National Renewable Energy Laboratory (2012)

- "The initial period of capital cost reductions came to an end in the early-to-mid 2000s."
- "An important exception to this trend [was] China."
- "The emergence of a handful of strong domestic [manufacturers led to] lower capital costs in China."

Reasons for this cost increase?

- Increased balance of plant and turbine prices (latter, mostly)
- Commodity and energy prices
- Huge growth in wind power (supply constraints)
- Labor costs
- Turbine upscaling and changes in design

What use are these learning curves?



Junginger M et al. (2008) Technological learning in the energy sector. Utrecht University and the Energy Research Center of the Netherlands.

Cottage industry calculating these LRs

Azevedo I et al. (2013) Technology Learning Curves and the Future Cost of Electric Power Generation Technology. Presentation to the EPRI 18th Annual Energy and Climate Change Research Seminar (Washington, DC).

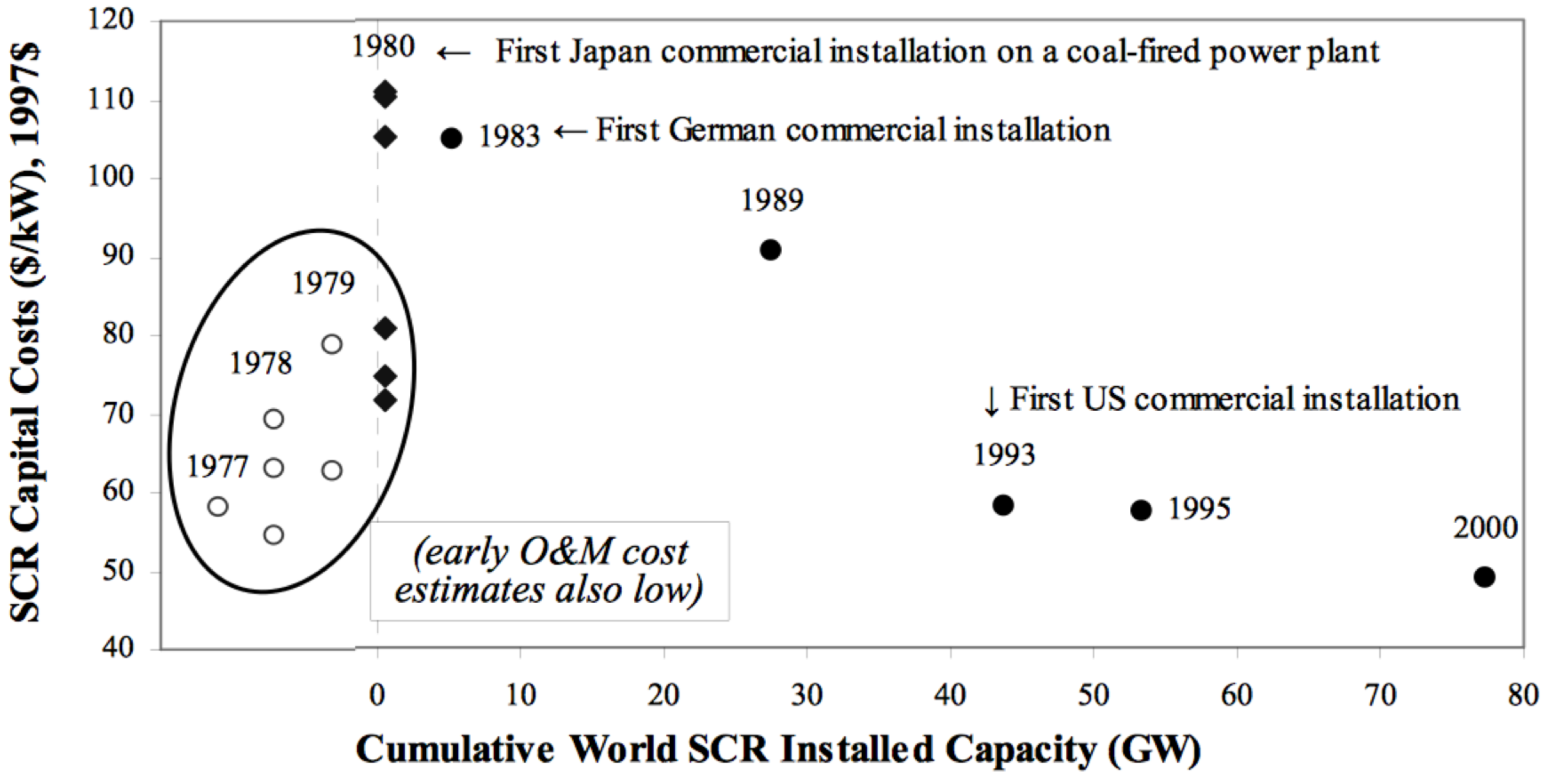
Technology	Number of studies reviewed	Number of studies with one factor	Number of studies with two factors	Range of learning rates for "learning by doing" (LBD)	Range of rates for "learning by researching" (LBR)	Years covered across all studies
Coal					Two-factor models	
PC	2	2	0	5.6% to 12%		1902-2006
IGCC	1	1	0	2.5% to 7.6%		(projections)
Natural Gas	8	6	2	0.65% to 5.3%	2.4% to 17.7%	1980-1998
Nuclear	4	4	0	<0% to 6%		1975-1993
Wind (on-shore)	35	29	6	-3% to 32%	10% to 23.8%	1980-2010
Solar PV	23	22	1	10% to 53%	10%	1959-2001
BioPower						
Biomass production	4	4	0	12% to 45%		1971-2006
BioPower generation	7	7	0	0% to 24%		1976-2005
Geothermal power	3	0	0			1980-2005
Hydropower	3	0	2	0.5% to 11.4%	2.6% to 20.6%	1980-2001

Limitations of the learning curve model

- Simplistic: focuses only on production costs, and needs virtually impossible decomposition into learning associated with specific processes:
  - Learning by researching
  - Learning by building
    - Technological, financial, social
  - Learning by operating
- Sheds no light on what might be driving costs
- System boundaries (incl. geography) must be delineated
- Leads to silly discussions (e.g. getting the installation costs of solar, which start to dominate system costs, down)

Assessments reveal non-monotonicity

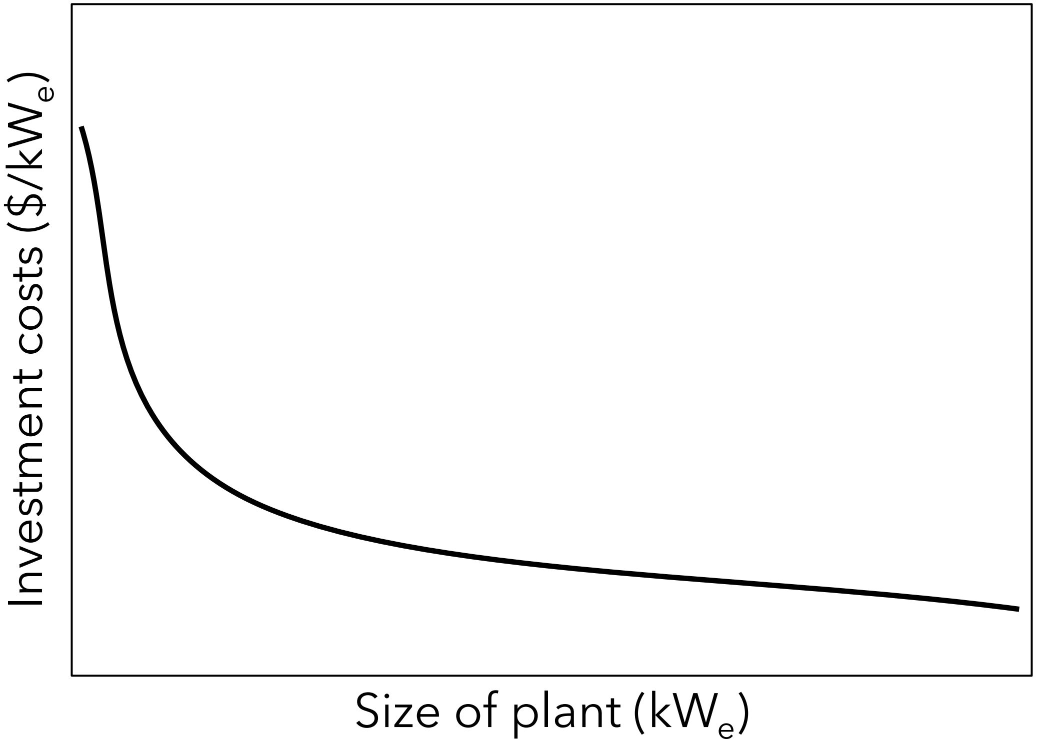
- Increases in the costs of early projects as kinks worked out



Rubin ES (2010) Uncertainty in Experience Curves for Climate Policy Analysis: Some insights from case studies. Presentation to the NAS Workshop on Modeling the Economics of Greenhouse Gas Mitigation. (Washington, DC).

Economies of scale

- Microeconomic concept that originated with Adam Smith's theory on the division of labor. Suggests that cost advantages accrue due to size.



The classic economies of scale model

$$E = a\,C^{b}$$

where	***E***	is	the cost to produce a piece of equipment
	a	is	a coefficient
	C	is	the capacity of the piece of equipment
	b	is	the scaling parameter

$$C_2 = C_1\,(X_2 / X_1)^{b}$$

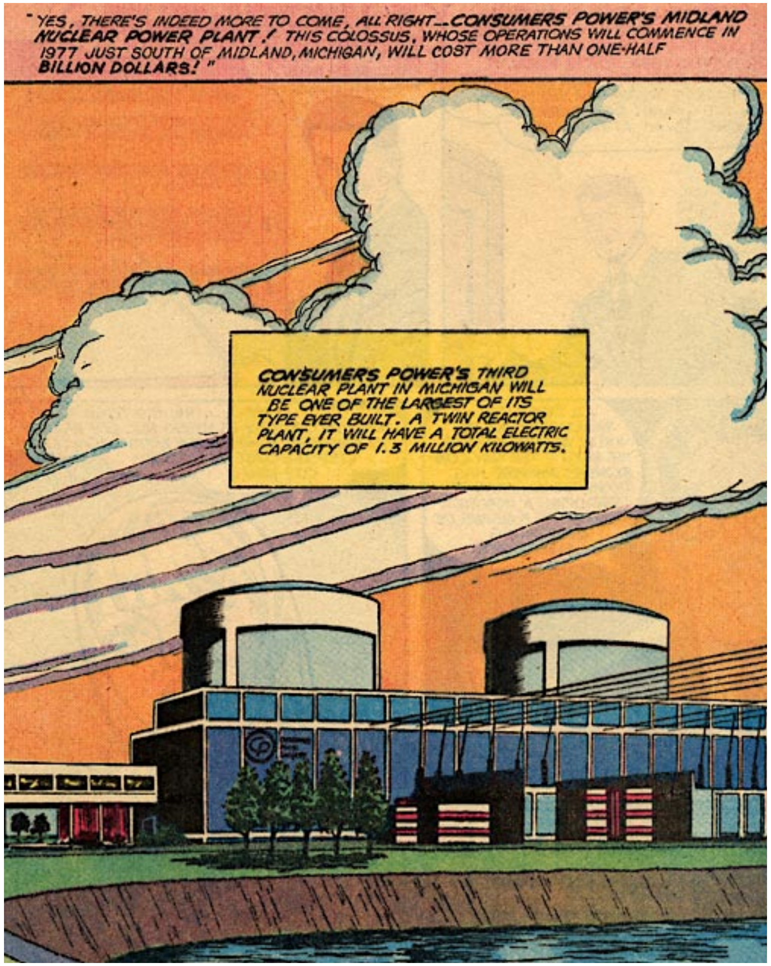
The ".6 rule"

where	C_1 *and* C_2	are	the costs of two pieces of equipment
	X_1 *and* X_2	are	their capacities
	b	is	the scaling parameter
			0.6 is the classic scaling parameter

Engineers went to extremes

"The competition to build ever larger plants reached absurd proportions: by 1968, manufacturers were taking orders for plants six times larger than the largest one then in operation."

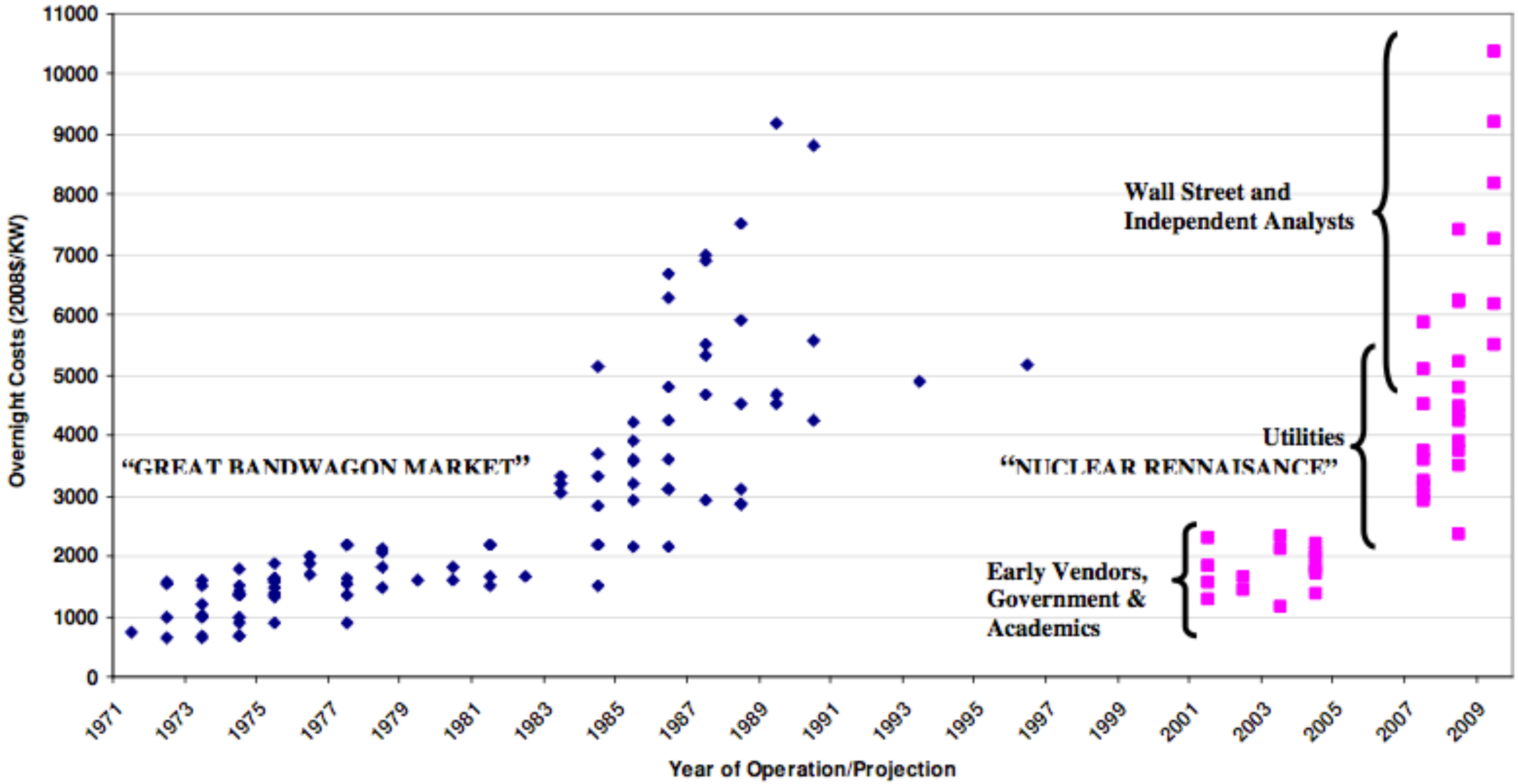
"the company's main asset, a nuclear power plant under construction in Michigan, became entangled in regulatory and financial disputes and construction problems. Financial disaster seemed imminent when it abandoned the nuclear plant after spending $4.1 billion on it."



Bupp IC and Derian J (1978) *Light Water: How the Nuclear Dream Dissolved.*. Basic Books, NY: 73-74

Hylton RD (1989) Market Place; Nuclear Write-Off To Success Story. *The New York Times.* http://www.nytimes.com/1989/09/25/business/market-place-nuclear-write-off-to-success-story.html

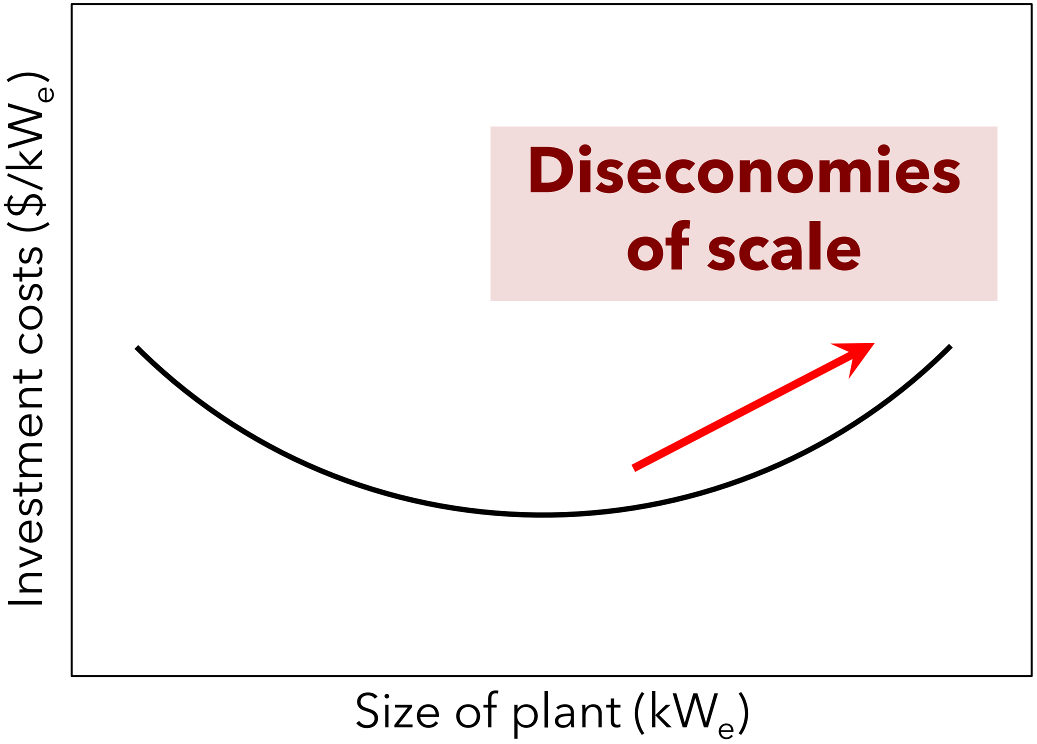
Technologies "virtually unconstructable"



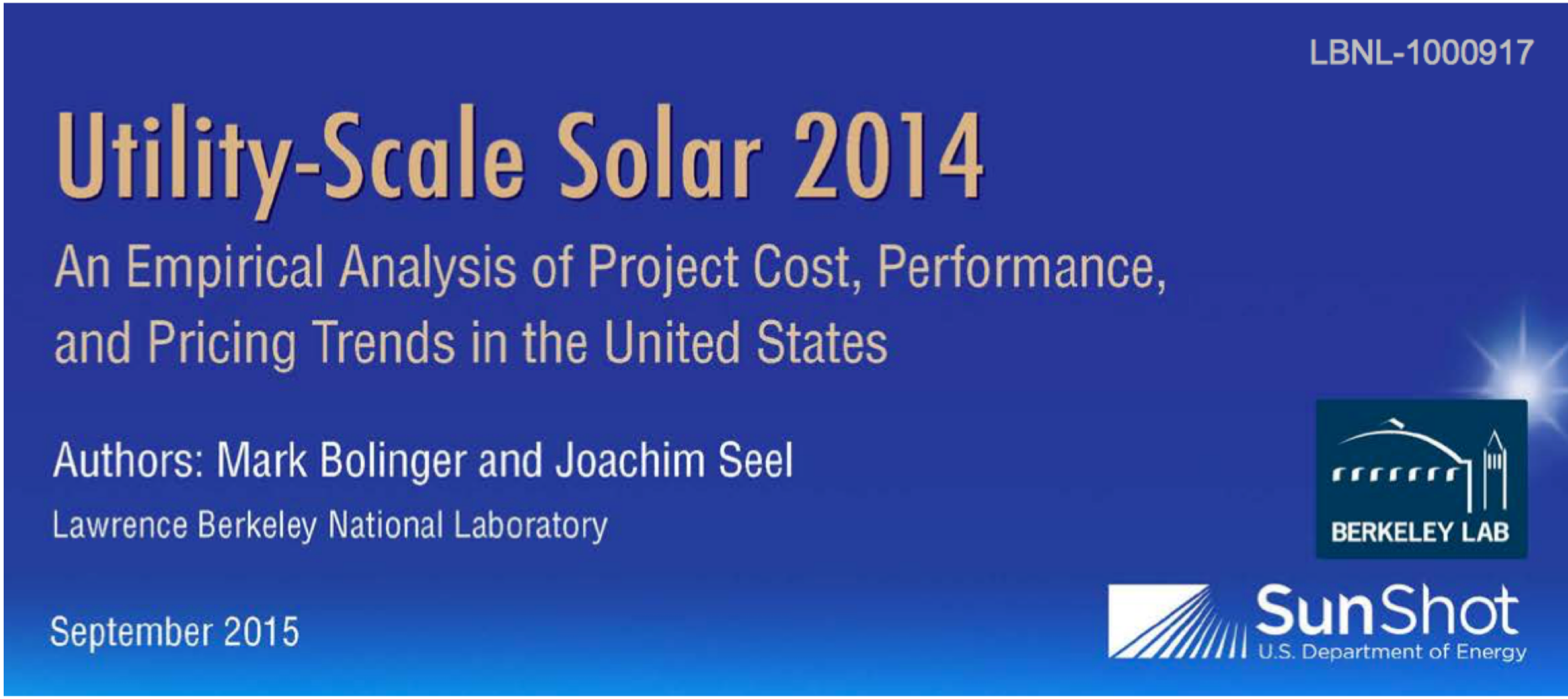
Cooper, M. The Economics of Nuclear Reactors: Renaissance or Relapse? Institute for Energy and the Environment, Vermont Law School [Internet]. 2009 June [cited 2011 November 17]. Figure ES-1.

Economics of scale doomed industry

- Based on a misunderstanding of basic economic theory

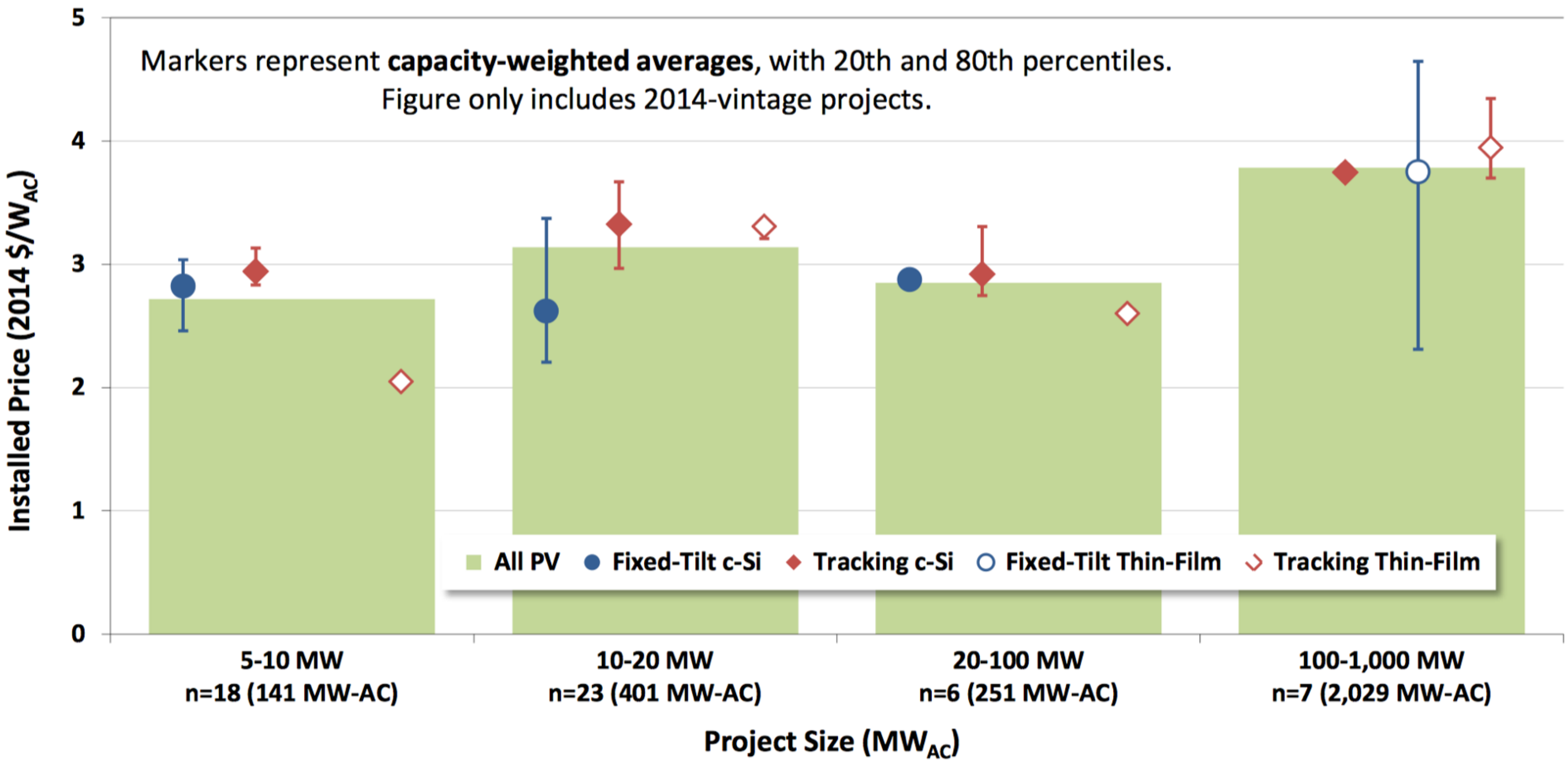


Problem not restricted to nuclear power



Bolinger M, Seel J (2015) Utility-Scale Solar 2014: An Empirical Analysis of Project Cost, Performance, and Pricing Trends in the United States. Lawrence Berkeley National Laboratory.

"No…evidence of economies of scale"



Bolinger M, Seel J (2015) Utility-Scale Solar 2014: An Empirical Analysis of Project Cost, Performance, and Pricing Trends in the United States. Lawrence Berkeley National Laboratory.

Problems in technology diffusion

- Even after emergent energy technologies are adopted, they can sometimes become victims of their own success:
  - Financial incentives, such as feed-in-tariffs, can grow substantially and stress the public purse

    Japan and Germany

  - Their variability and intermittency leads to reliability concerns

    South Australia and Ontario

  - Small operating costs challenge the entire power system, and require rejigging the whole power market to ensure the reliability of supply

    The merit-order effect

Variability is only a challenge…

…if you don't have institutions with the foresight to ameliorate or eliminate it. (In rapaciously capitalist economies, this is generally the case)

- Belief that variability can be addressed by transmission:

Supplying Baseload Power and Reducing Transmission Requirements by Interconnecting Wind Farms

CRISTINA L. ARCHER AND MARK Z. JACOBSON

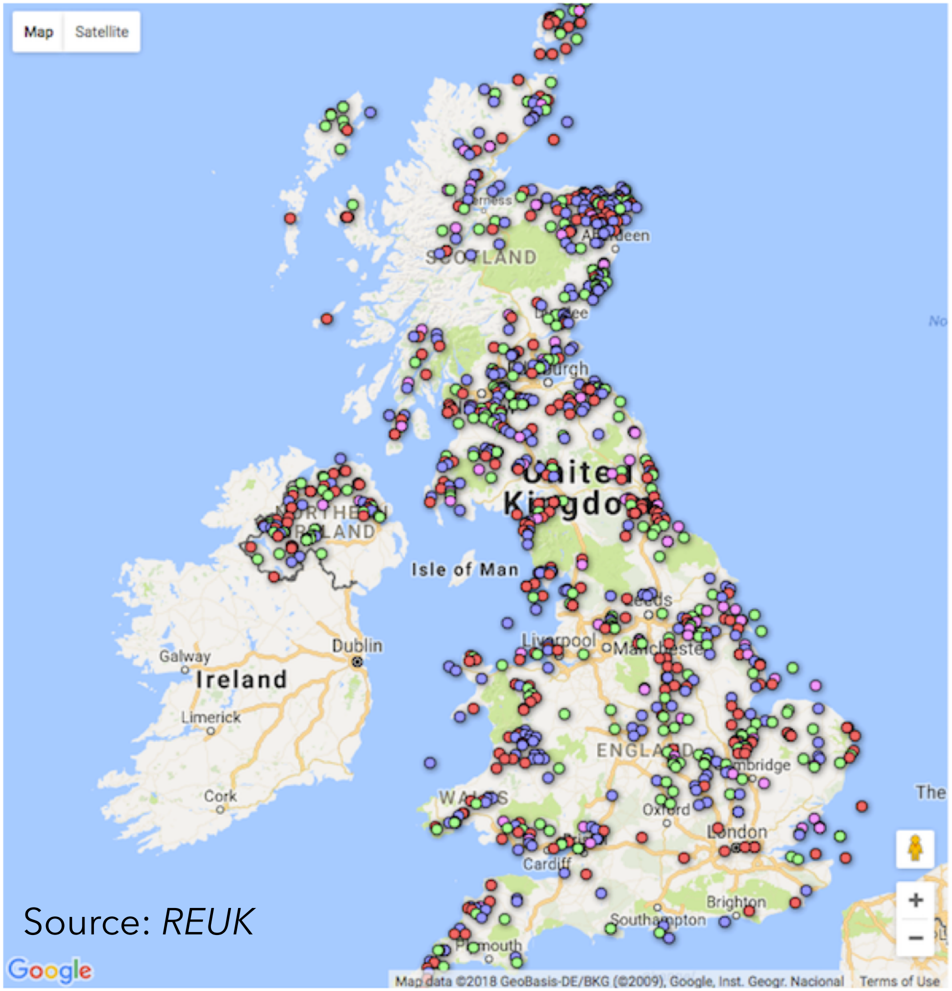
Department of Civil and Environmental Engineering, Stanford University, Stanford, California

- Interconnection good, but assuming that wind farms in different geographic areas will supply base load, especially based on small wind speed data sets, is foolhardy

Geographic dispersion not a solution!

- Geographic diversity to smooth variability
- The UK's system operator is routinely curtailing **100-300GWh** of wind power per month.
- Costing rate payers millions

Source: *Schell K (2018)*



Source: *REUK*

Problem is one of poor institutions

- Mostly, siting of wind farms is based on National Renewable Energy Laboratory mean annual wind speed data
- But there are wind droughts, many in places with high resources. These get their wind resource in short bursts of extremely high wind. Other areas have lower mean wind speeds, but little drought

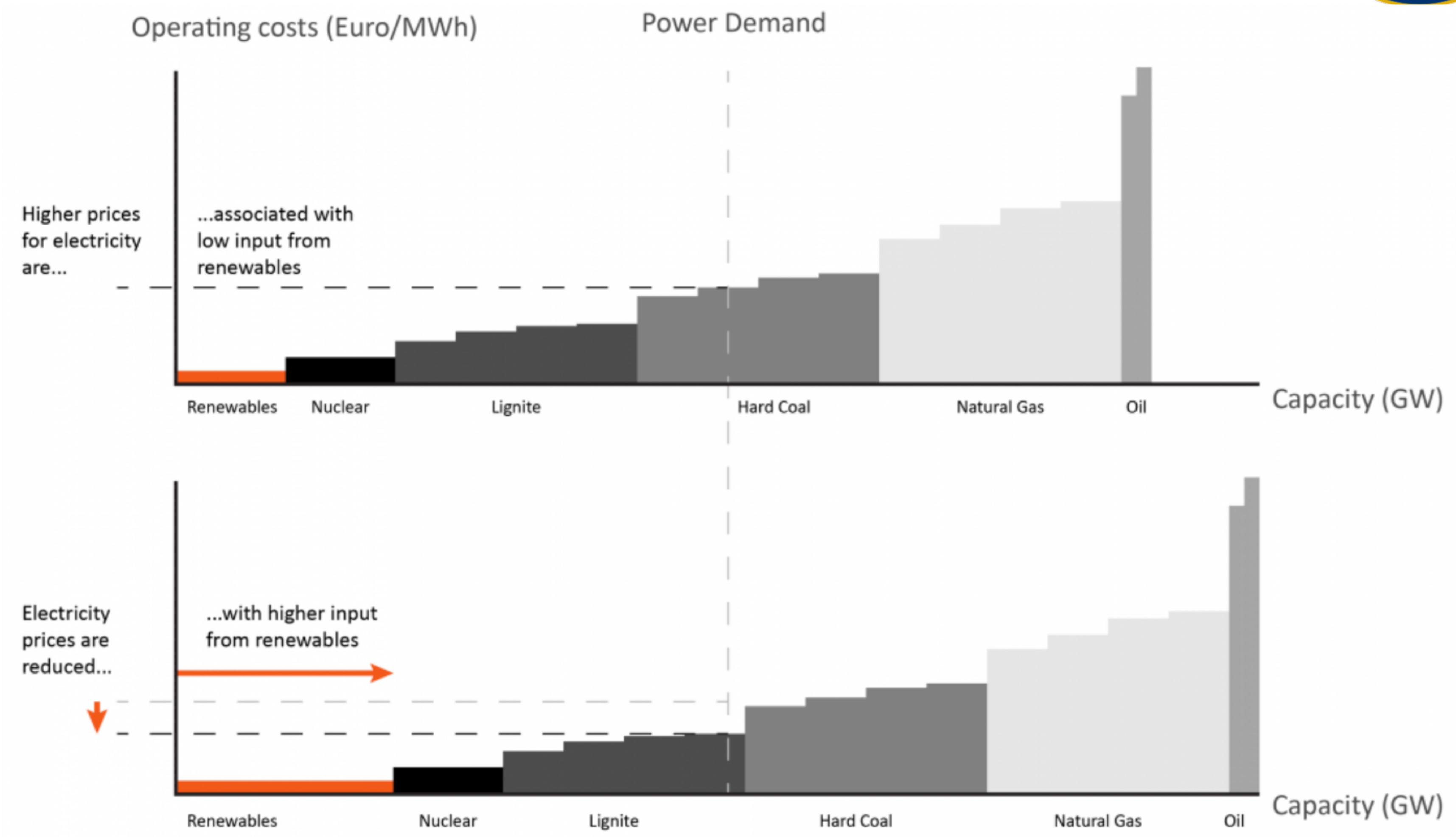
Power system dynamics due to TX wind

- Enormous influx of wind capacity:
  - Required much investment in transmission
  - Led to wind curtailment, drove $ to negative territory
- Why is this happening?
  - Investment tax credits are given to investors for building wind farms, regardless of location
  - Production tax credits are important, but focus on mean annual wind speed
  - No mention of **variability** of power due to drought
  - This issue might be of no (or little) important to investors, but **extremely** important to power system operators

The merit-order effect

- The merit order is the mechanism by which electricity market prices are set
- Generators bid-in with their cost of generation
- Lower-cost generators supply electricity first
  - Renewables are non-dispatchable sources of electricity
  - There is no storage, so arbitrage not (yet) possible
  - Institutions can also mandate renewables take-off

The merit-order effect with renewables

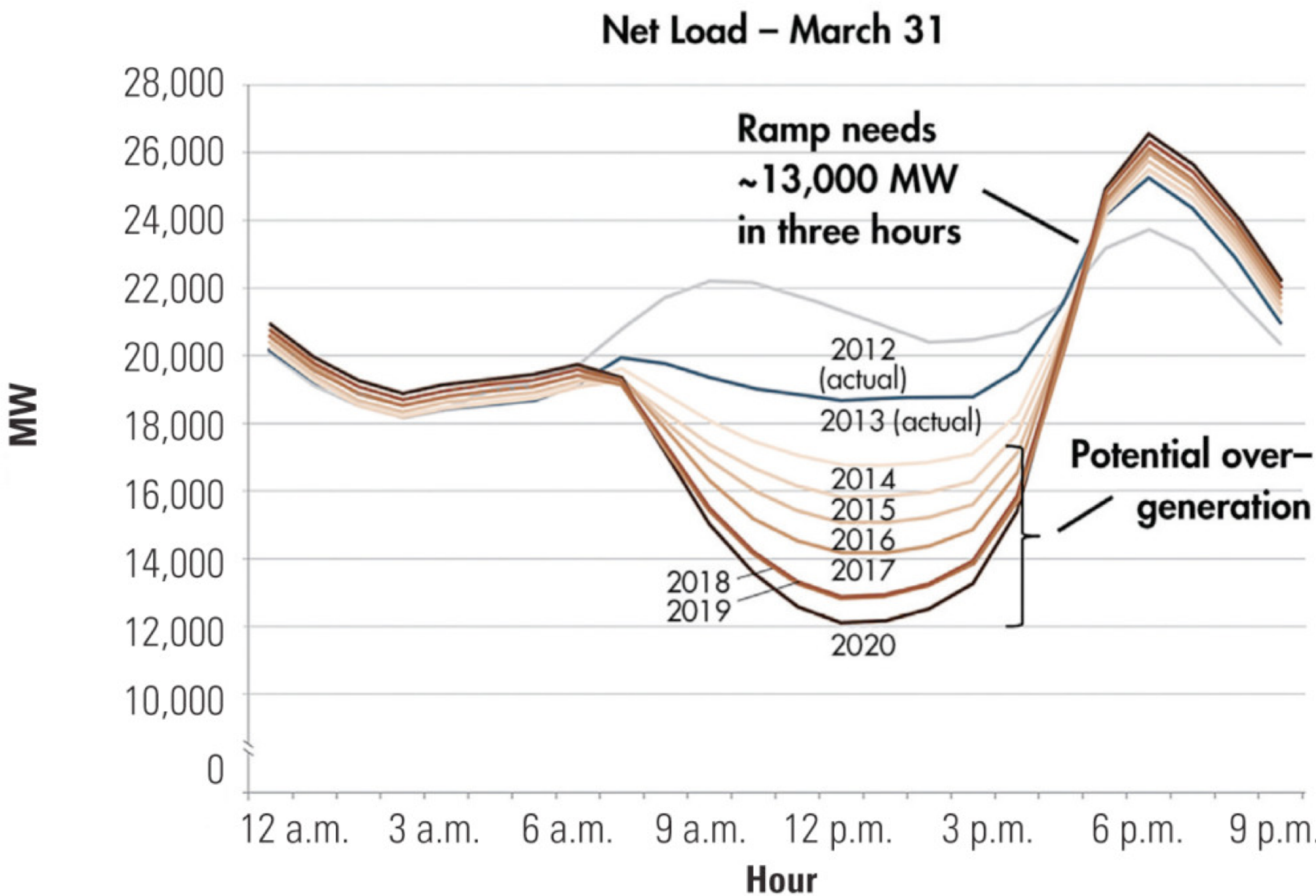


https://www.cleanenergywire.org/factsheets/setting-power-price-merit-order-effect

Renewables penetration warps markets

- The more renewables penetrate the market, the more they depress wholesale electricity prices (the duck curve)
- The merit order is now a **dynamic** utilization curve
- Eventually, some generators cannot compete, especially if flexibility becomes a valued trait
- Need to be given financial guarantees to maintain their plants, just in case of wind droughts or intense demand
  - Nuclear power plants in highly competitive markets, which have very low operating costs, are shutting down
- They also affect the demand load profiles; hence the emergence of the duck curve, due to solar generation

The solar "duck curve" in California



http://www.powermag.com/duck-hunting-california-independent-system-operator/

Conclusions

- Technology adoption and diffusion are studied using a range of methods, all of which have more than their fair share of weaknesses
- These tools are important, despite their weaknesses, for evaluating future energy systems
- Important to draw system boundaries and caveat analysis where any doubts linger

If you think technical challenges are great, wait until you encounter the economic ones

If you think economic challenges are great, wait until you face the political and behavioral constraints