Patterns of technological evolution

Bariloche complex systems summer school
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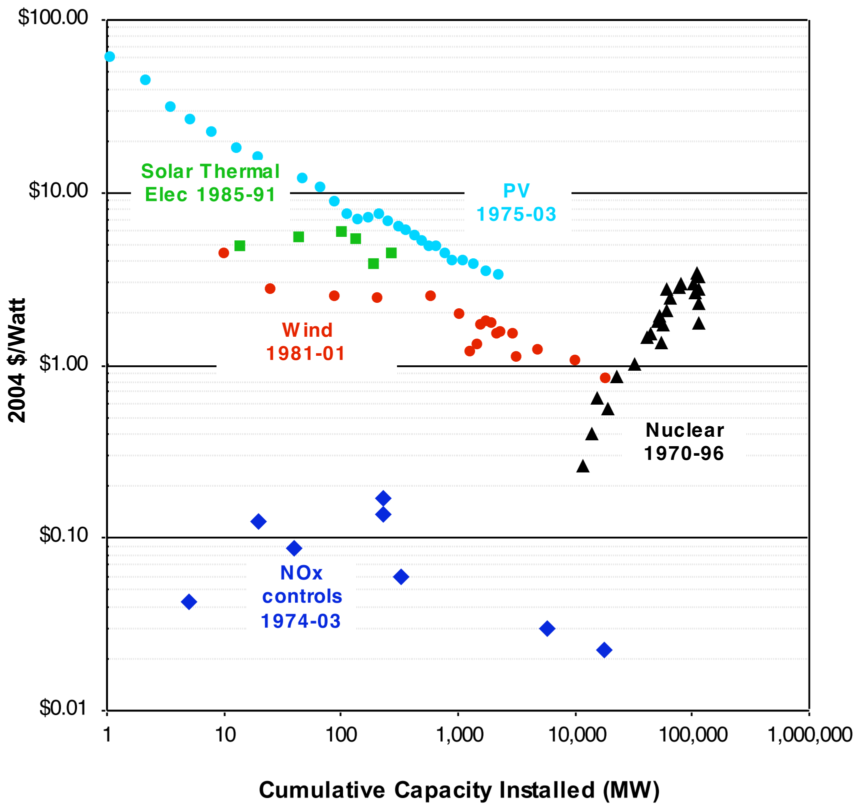
J. Doyne Farmer
Santa Fe Institute
LUISS Guido Carli
(original results are joint work with Jessika Trancik and James McNerney)

Outline

- Are there patterns in technological evolution and improvement?
- Can they be used to forecast technological trajectories?
  - example of electricity production from coal
- Can this be used to allocate investment?
- How to discount the future?

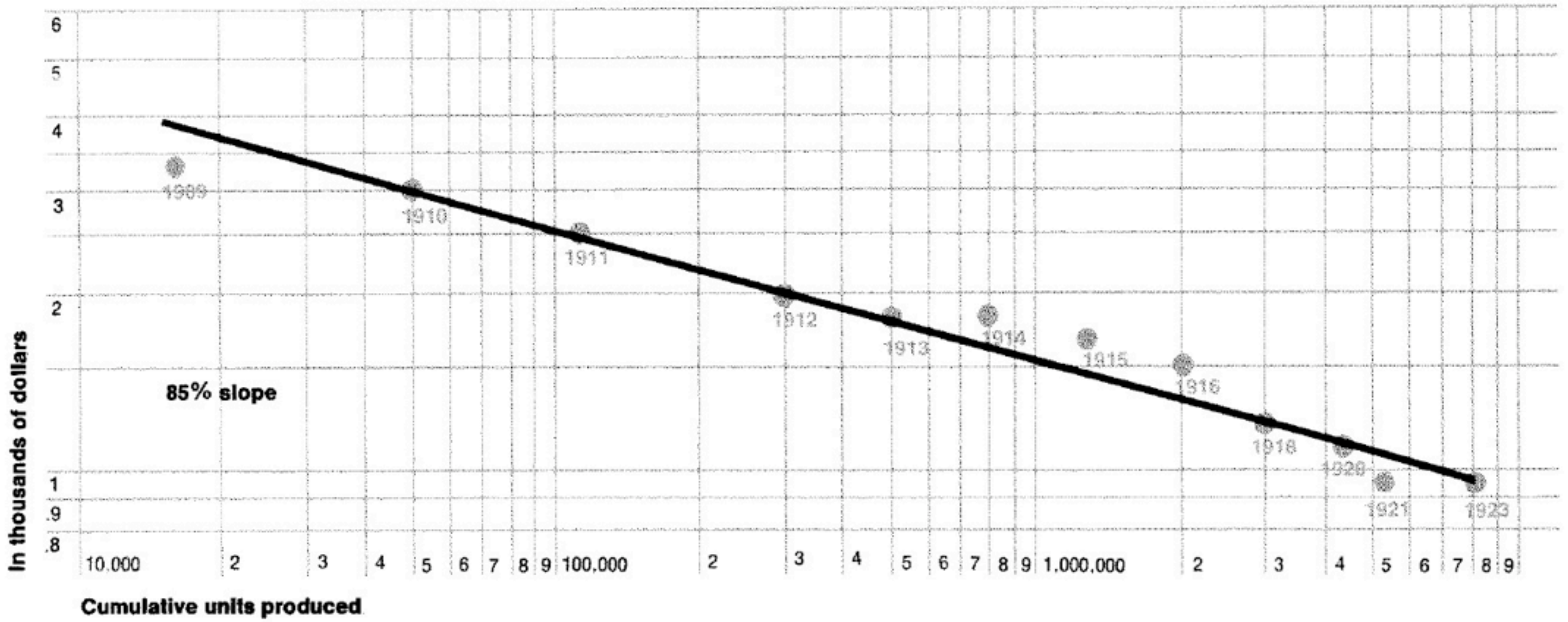
Performance curves

- Worker output in airplane manufacturing (Wright, 1936)
- Cost of a technology across entire industry (BCG, 1968)
- Observed for aggregates of technologies and diverse metrics
- Functional form assumed: $y=ax^{-b}$ and *Progress ratio* $= 2^{-b}$
- Used to predict future costs
- How reliable are projections?
- How to design portfolios?

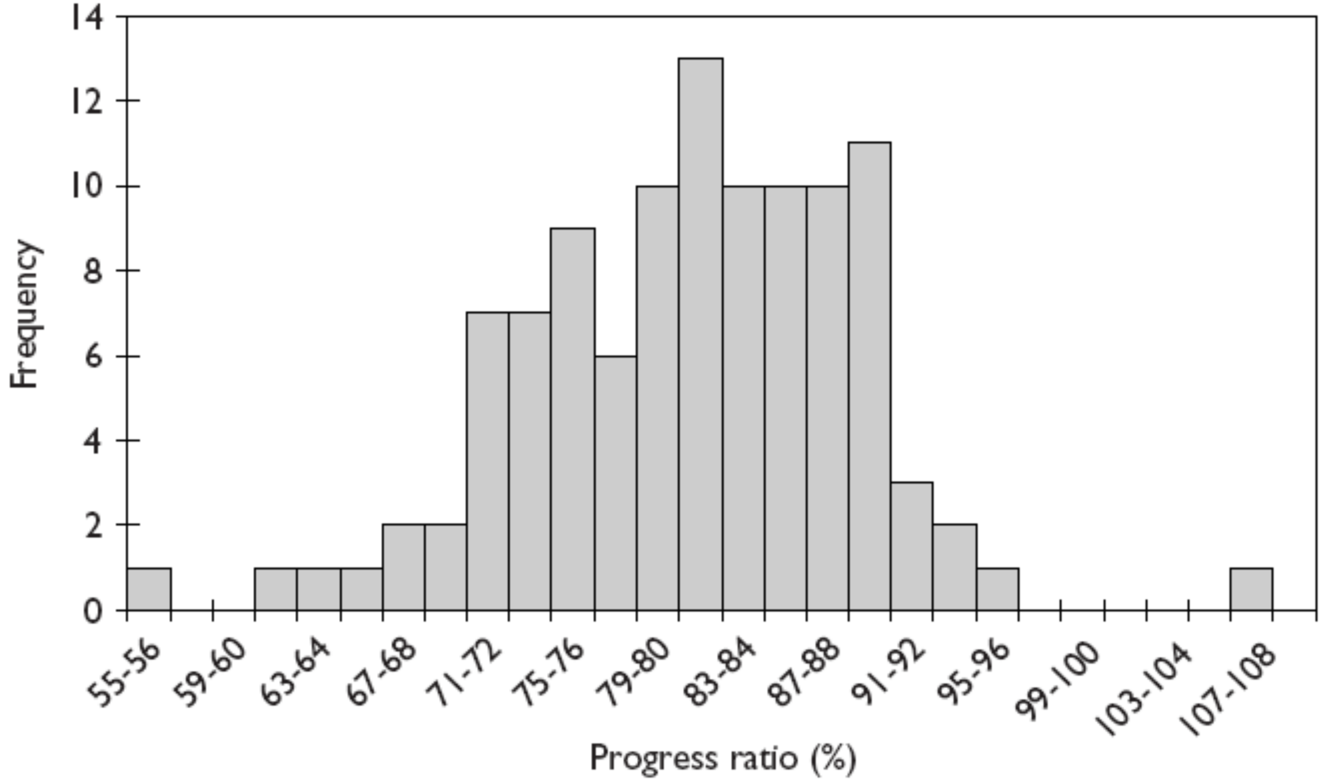


(Nemet, *Energy Policy*, 2007)

Exhibit I
Price of Model T, 1909-1923 (Average list price in 1958 dollars)



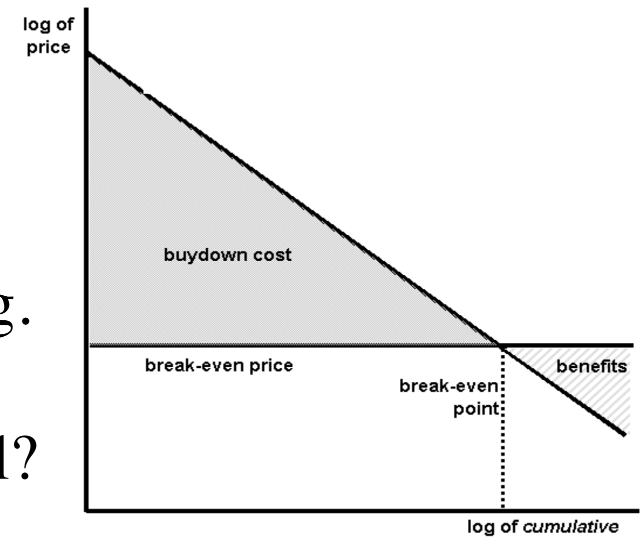
Diversity of performance ratios



Progress ratios 108 cases, 22 field studies, electronics, machine tools, system components for electronic data processing, papermaking, aircraft, steel, apparel, and automobiles (Dutton and Thomas, 1984)

Cross-over sensitively depends on progress ratio

- Under assumptions about progress ratios, can estimate cost of achieving parity between two technologies. E.g. what is capacity increase needed to break even with coal?
- Very sensitive to PR:
    - 0.75 => 30B
    - 0.8 => $60B
    - 0.85 => $300B



(Duke, RFF presentation, 2003)

Performance curves -data problems

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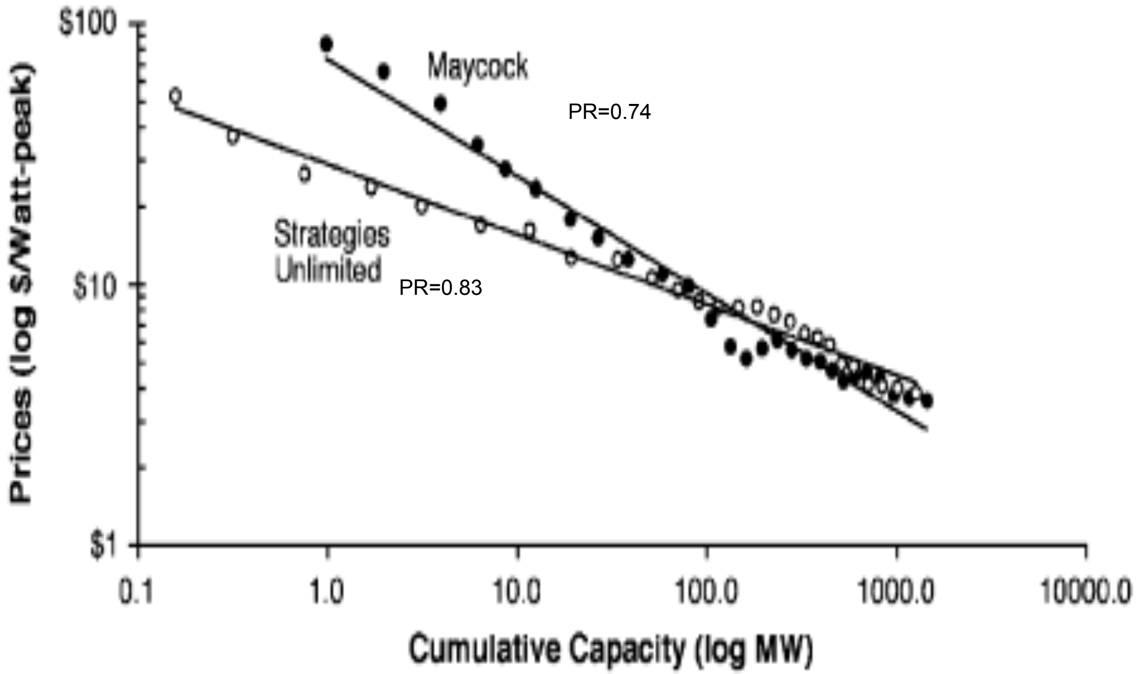
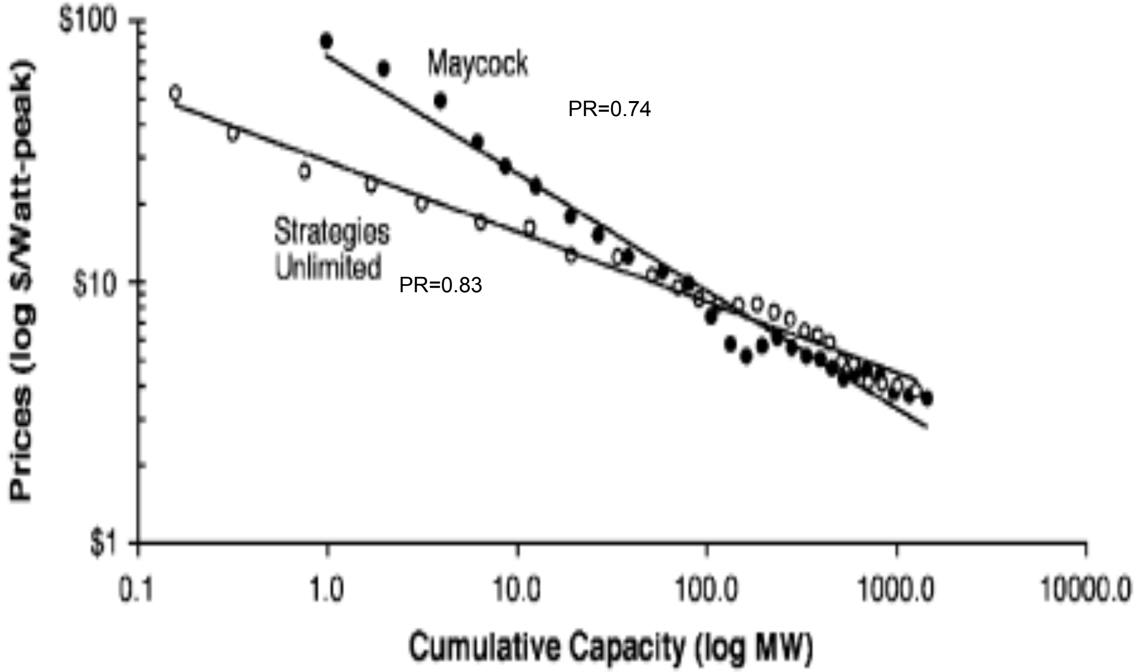
- Data discrepancies / curve fitting (lack of out-of-sample testing)



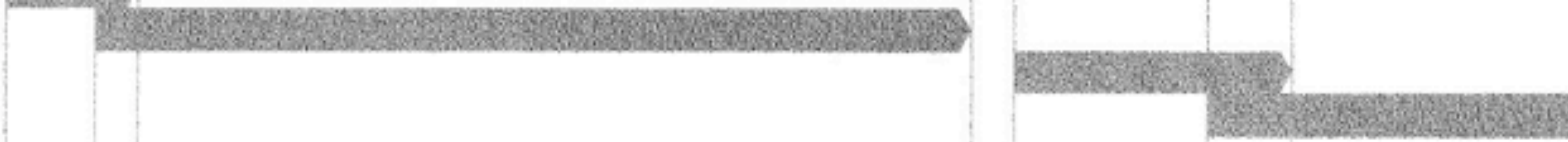
Photovoltaics performance curves (Nemet, *Energy Policy*, 2006)

Performance curves -data problems

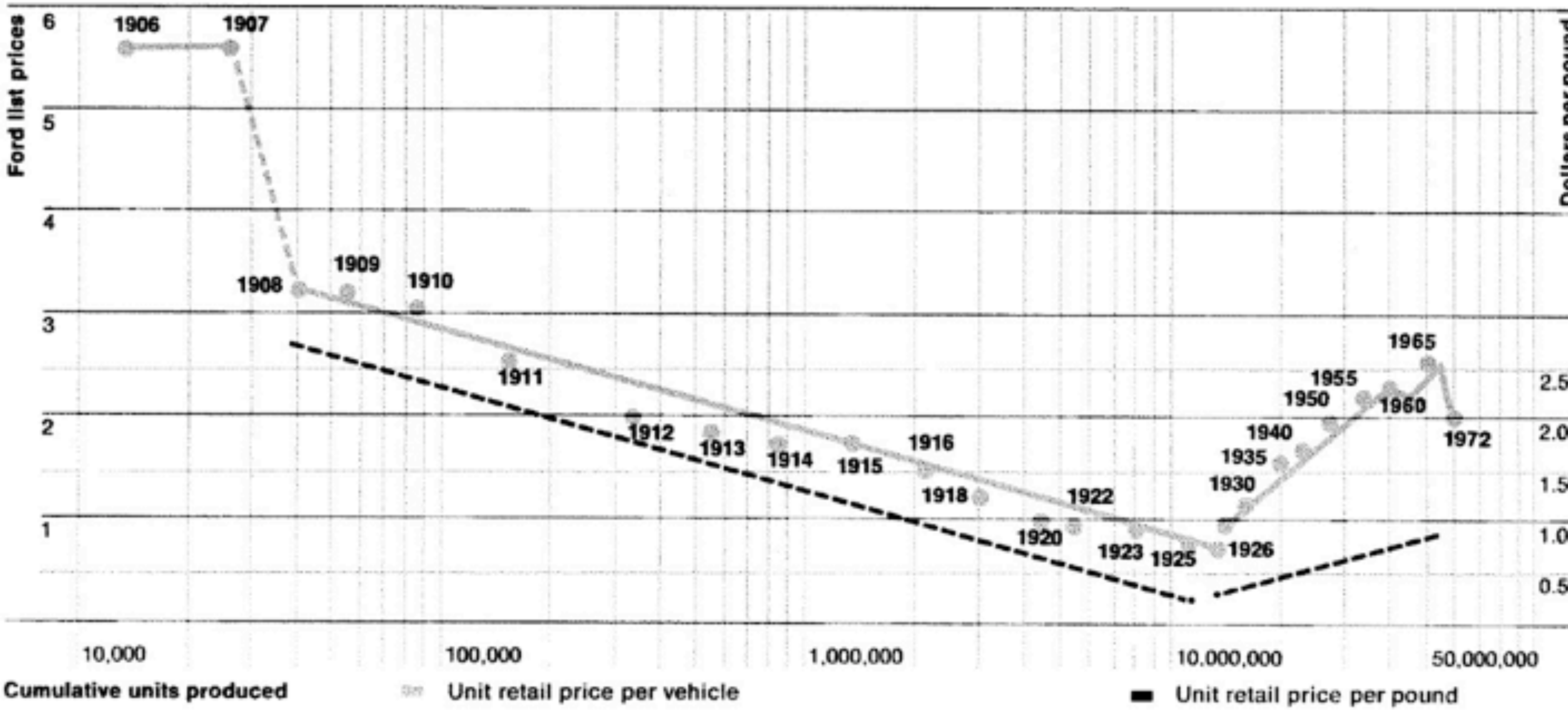
- Data discrepancies / curve fitting (lack of out-of-sample testing)
- Price data vs. cost data



Photovoltaics performance curves (Nemet, *Energy Policy*, 2006)



Models	ABCNRSK	T	A	Annual model changes
Engines (H.P.)	2 (15 & 50)	1 (20)	1 (24)	2 or more (50 & more)
Wheel bases	2	1	1	2 or more
Weights	Up to 1800	1100-1820	2312 (average)	2335 and up (average)



What drives improvement? Process decomposition

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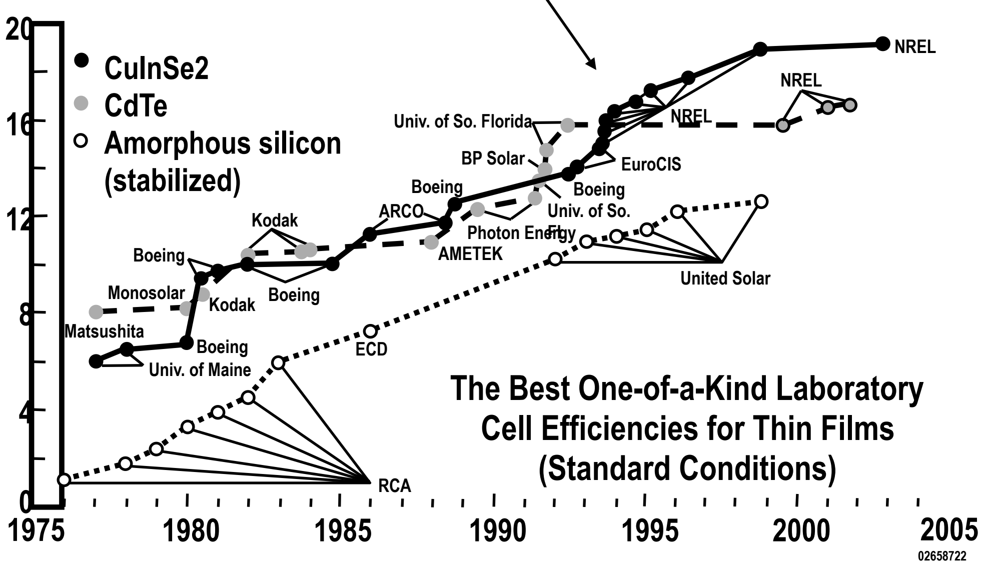
Most important factors for PV improvement (Nemet, 2006):

- Module efficiency (innovation)
- Plant size (economies of scale)
- Cost of silicon

Summary of model results, 1975–2001

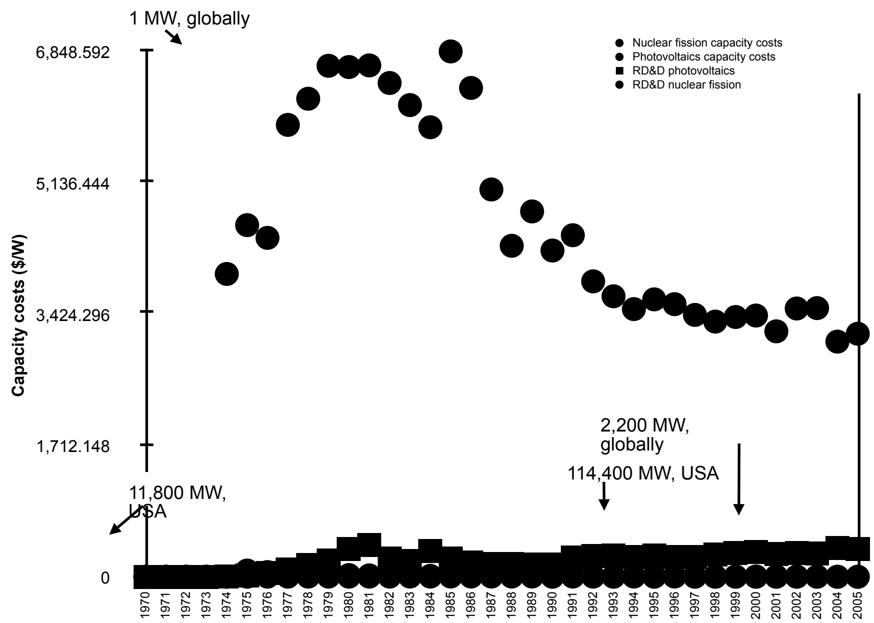
Factor	Change	Effect on module cost ($/W)
Module efficiency	6.3% → 13.5%	−17.97
Plant size	76 kW/yr → 14 MW/yr	−13.54
Si cost	300 $/kg → 25 $/kg	−7.74
Si consumption	30 g/W → 18 g/W	−1.06
Yield	87% → 92%	−0.87
Wafer size	45 cm^2 → 180 cm^2	−0.67
Poly-crystal	0% → 50%	−0.38
Sum of factors		−42.24
Actual change		−70.36
Residual		−28.13



(Trancik and Zweibel, *IEEE WCPEC*, 2007)

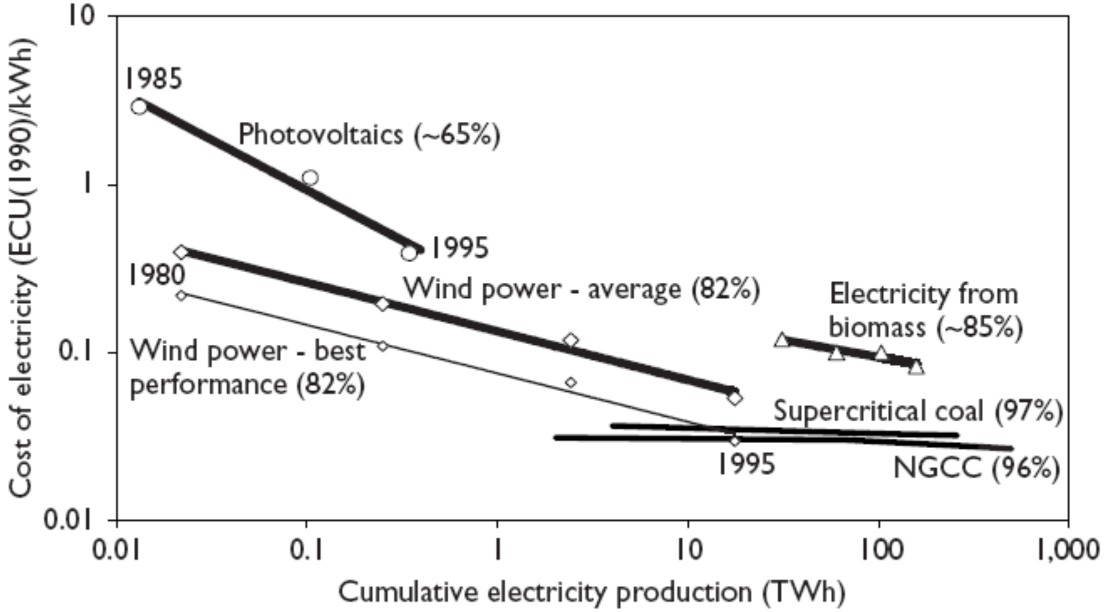
Input decomposition

Do technologies with lower unit scale have better progress ratios?
Does this make RD&D more effective?
- E.g., nuclear fission vs. photovoltaics



(Trancik, *Environmental Research Letters*, 2006)
Data: IEA, RD&D Database, 2005; G. F. Nemet, PhD Dissertation, University of California, 2007;
E. Kahn, “Electricity Utility Planning and Regulation”, American Council for an Energy Efficient Economy, 1991; EIA, “Monthly Energy Review: Table 8.1. Nuclear Energy Overview”, 2006.

Comparison of performance curves



Performance curves for the EU 1980-1995 (IEA, 2000)

What causes Wright's law?

Most thinking: some form of regularity about search. Cumulative production is proxy for number of search steps.

- Sahal: Double exponentials.
- Muth (1986): Random search, extreme value theory
- Auerswald, Kauffman, Lobo and Shell (2000) recipes with interdependent parts.
- Increasing returns (new but trivial)

- Double exponentials

$$\begin{aligned} x(t) &= \exp(at) \\ y(t) &= \exp(-bt) \\ y(x) &= x^{-b/a} \end{aligned}$$

-

Muth (1986)

- Cost reductions are realized through random search. Cumulative distribution of costs F(x).
- Lower cost techniques are adopted when discovered.
- Distribution of costs approaches a power function at a lower bound of zero.

$$\lim_{x \to 0} \frac{F(x)}{x^k} = C$$

- Search is prompted by production activity.
- Results in power law with slope -1/k.

Auerswald et al.

$$\omega = (\omega_1, \ldots, \omega_n)$$

- Production recipe
- Labor costs are additive $$\phi(\omega) = \sum_{i=1}^{n} \phi^i(\omega)$$
- Each operation is cost affected by d operations.
- Innovation proceeds through a series of trials in which d operations omega_i are altered.

Design structure matrix

DSMによるプロセスの表記例

各タスクが必要とする情報の提供元

	A	B	C	D	E	F	G	H	I	J
A										
B	×						×			×
C	×									
D	×		×							
E			×	×		×	×		×	
F			×							
G						×				×
H		×							×	×
I			×	×	×		×			
J		×	×	×		×				

業務の流れ

各タスクが作成する情報の提供先

タスクBを処理するには、A、G、Jからの情報が必要となる。

タスクCが作成した情報は、
D、E、F、I、Jに渡される。

＜書き方＞
●A、B…Jは、開発プロセスを構成する各タスクを表します。
●行方向と列方向に、同じ順序でタスク名を記入します。
●タスク間の情報の流れを、マトリックスに×印で記入します。

Processes \ DATA	Customer	Customer Order	Delivery	Product	Supplier	Supplier Order
1.1 Maintain Customer Account	A.D	R	R			
1.2 Receive Orders	R. U	A. D	R	R		R
1.3 Plan/Monitor Sales	R	R	R	R	R	R
1.4 Plan Sales Calls	R.U	R	R	R		
2.1 Manage A/R	R	R. U	R			
2.2 Manage A/P				R	R	R. U
2.3 Perform Financial Analyses	R	R	R	R	R	R
3.1 Maintain Product Information				A. D	R	R
3.2 Receive Products				R. U	R	R. U
3.3 Ship Products	R	R. U	A. D	R. U	R	
4.1 Maintain Supplier Accounts				R	A. D	R
4.2 Analyze Suppliers				R	R	R
4.3 Place Orders				R	R	A. D

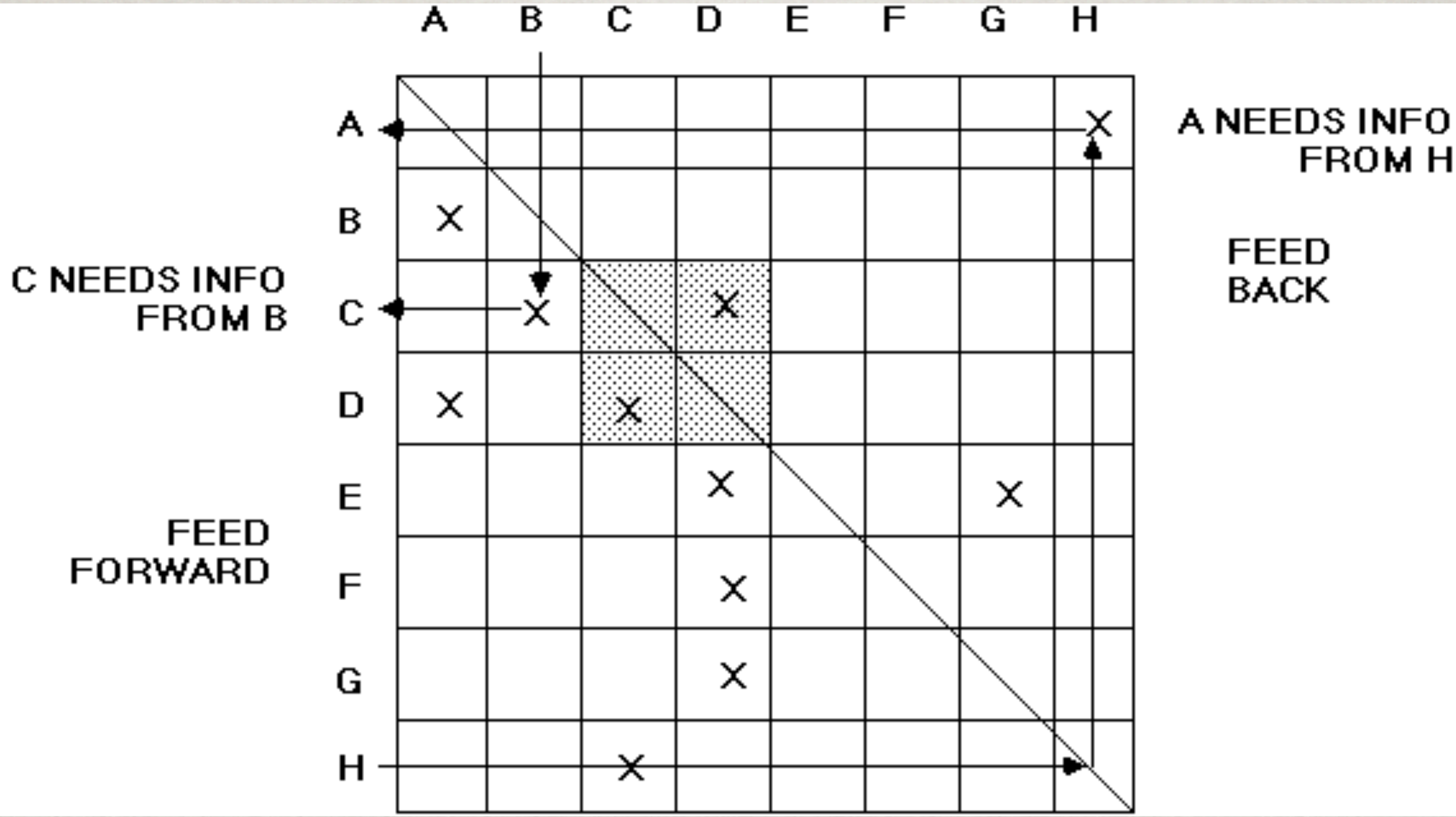
A = adds (creates) the data

R = retrieves/accesses the data

U = updates the data

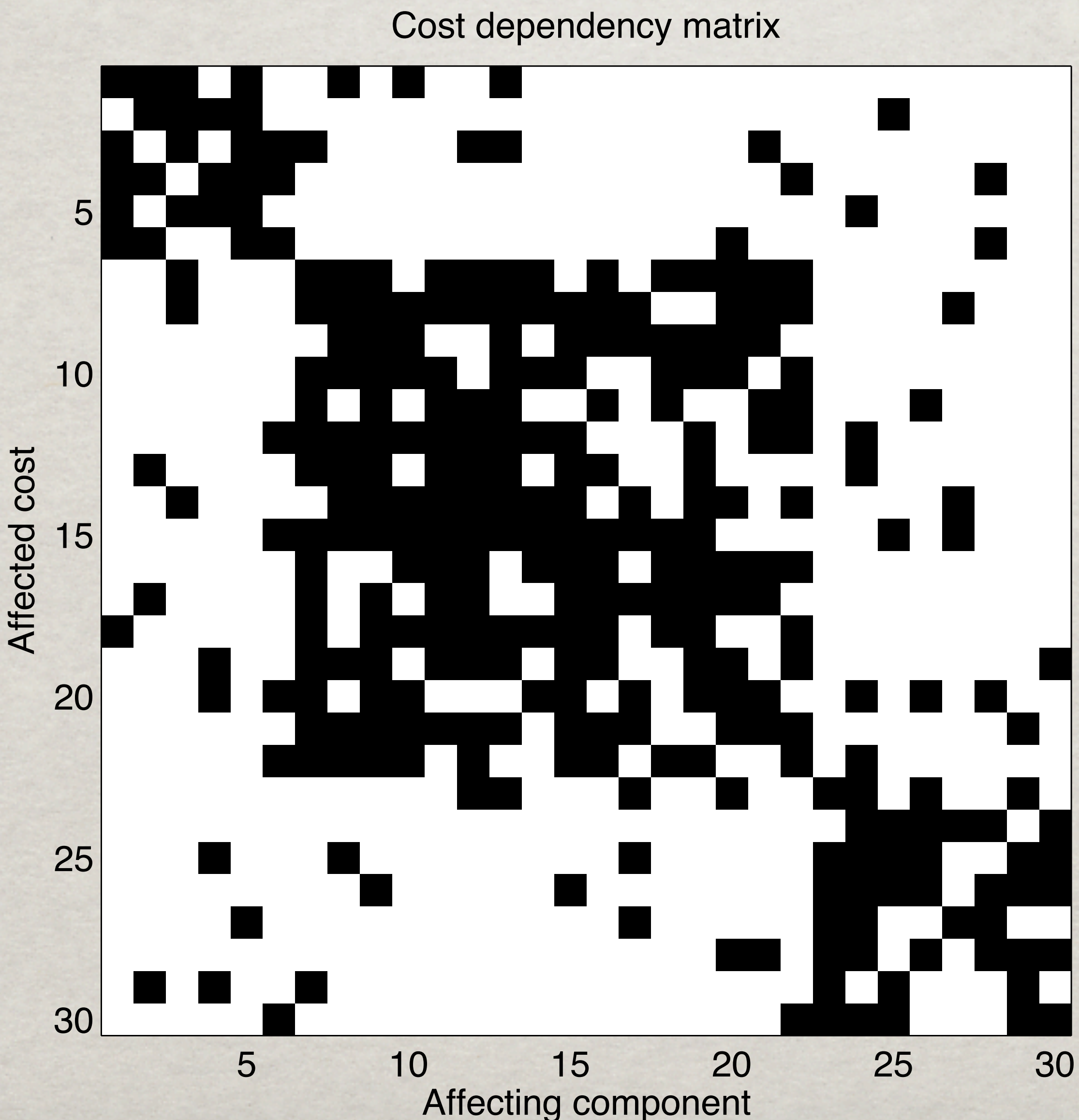
D = deletes the data

DSM

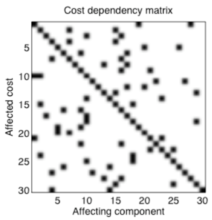


A B C D E F G H
A
B
C
D
E
F
G
H
A NEEDS INFO FROM H
FEED BACK
C NEEDS INFO FROM B
FEED FORWARD
X

Design structure matrix



The Production Recipe Model



Initialize dependency matrix
Initialize cost list

Cost list initial condition:

$$\left\{ \frac{1}{n}, \frac{1}{n}, \dots, \frac{1}{n} \right\}$$

For $y = 1$ to y_{max} {

- Pick a random component i
- Find other components $\{j\}$ affected by i
- $\{\phi'_j\} \leftarrow$ rand (ϕ_i drawn uniformly from $[0, 1/n]$)
- if $\sum_j \phi'_j < \sum_j \phi_j$

  $\phi_j \leftarrow \phi'_j$

}

$$\phi = \phi_1 + \phi_2 + \phi_3 + \phi_4 + \phi_5 + \phi_6$$

$$\phi' = \phi'_1 + \phi_2 + \phi'_3 + \phi'_4 + \phi_5 + \phi_6$$

$\phi' \lessgtr \phi \rightarrow$ keep changes / keep old recipe

Analysis

1 dependency:

$$\frac{d\phi}{dy} \propto -\phi\left(\frac{\phi}{2}\right) \quad \Rightarrow \quad \phi(y) \sim y^{-1}$$

- Size of reductions decreases exponentially, and it takes exponentially more time to reach reductions

d dependencies:

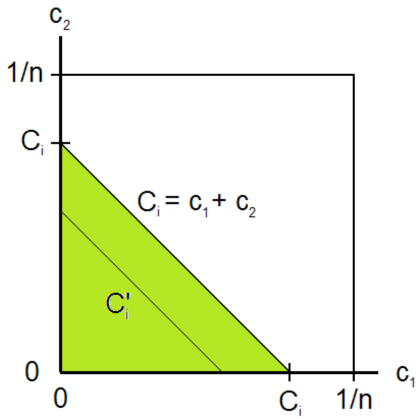
$$\frac{d\phi}{dy} \propto -p(\phi' < \phi)\left(\frac{\phi}{2}\right) \quad \Rightarrow \quad \phi(y) \sim y^{-\frac{1}{d}}$$

$$p(\phi' < \phi) \sim \phi^{d}$$

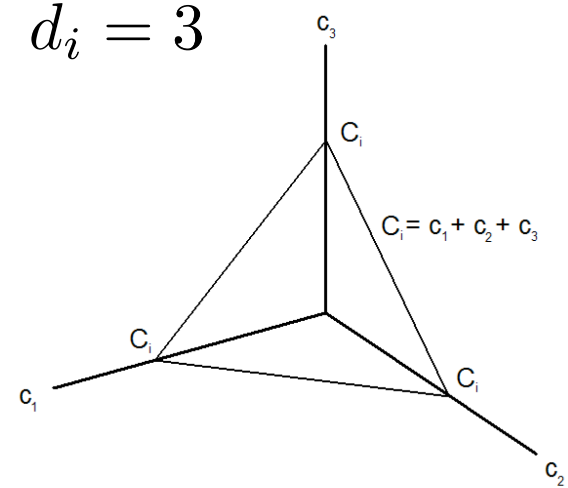
Importance of Out-degree

d_i = out-degree of component i

Example: $d_i = 2$



$d_i = 3$



Probability of achieving a cost reduction with component i

$$p_i = \frac{(nC_i)^{d_i}}{d_i!}$$

$$C_i = c_i + c_j + c_k + \cdots$$

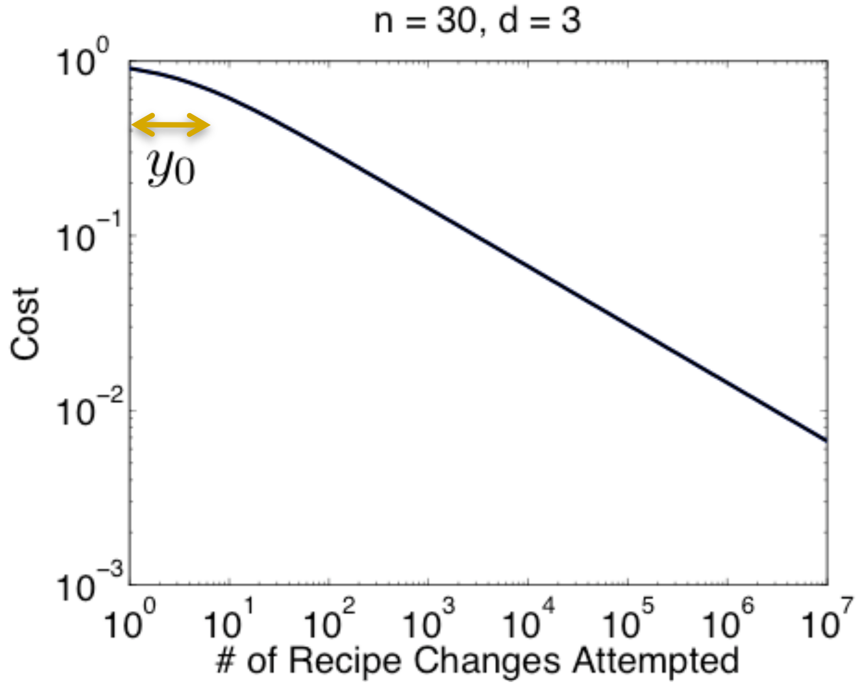
Analysis

- More carefully…

$$\frac{d\phi}{dy} \approx -\frac{d^{d+1}}{(d+1)!n}\phi^{d+1}$$

$$\phi(y) = \phi(0)\left(\frac{y}{y_0}+1\right)^{-\frac{1}{d}}$$

$$y_0 = \frac{1}{\phi(0)^d}\frac{(d+1)!}{d^{d+2}}n$$



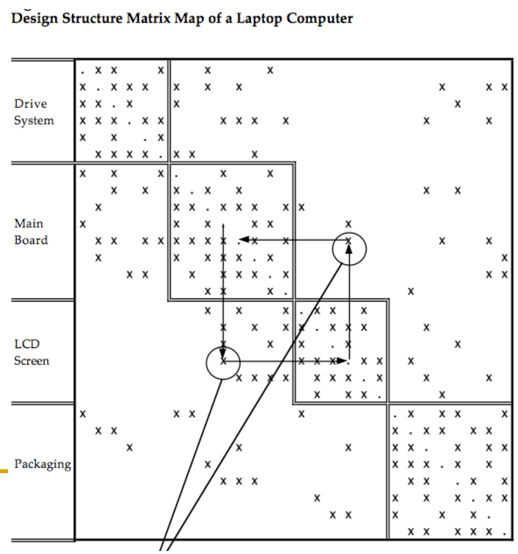
Connection to Engineering

$$\phi(y) \sim y^{-\frac{1}{d}}$$

- Testable prediction:

  greater modularity → faster cost reduction
- Design structure matrices (DSM)

DSM of a laptop computer:



d	Progress Ratio 2^(-1/d)
1	50.0 %
2	70.7 %
3	79.4 %
4	84.1 %
5	87.1 %
10	93.3 %
20	96.6 %
40	98.3 %

Increasing returns

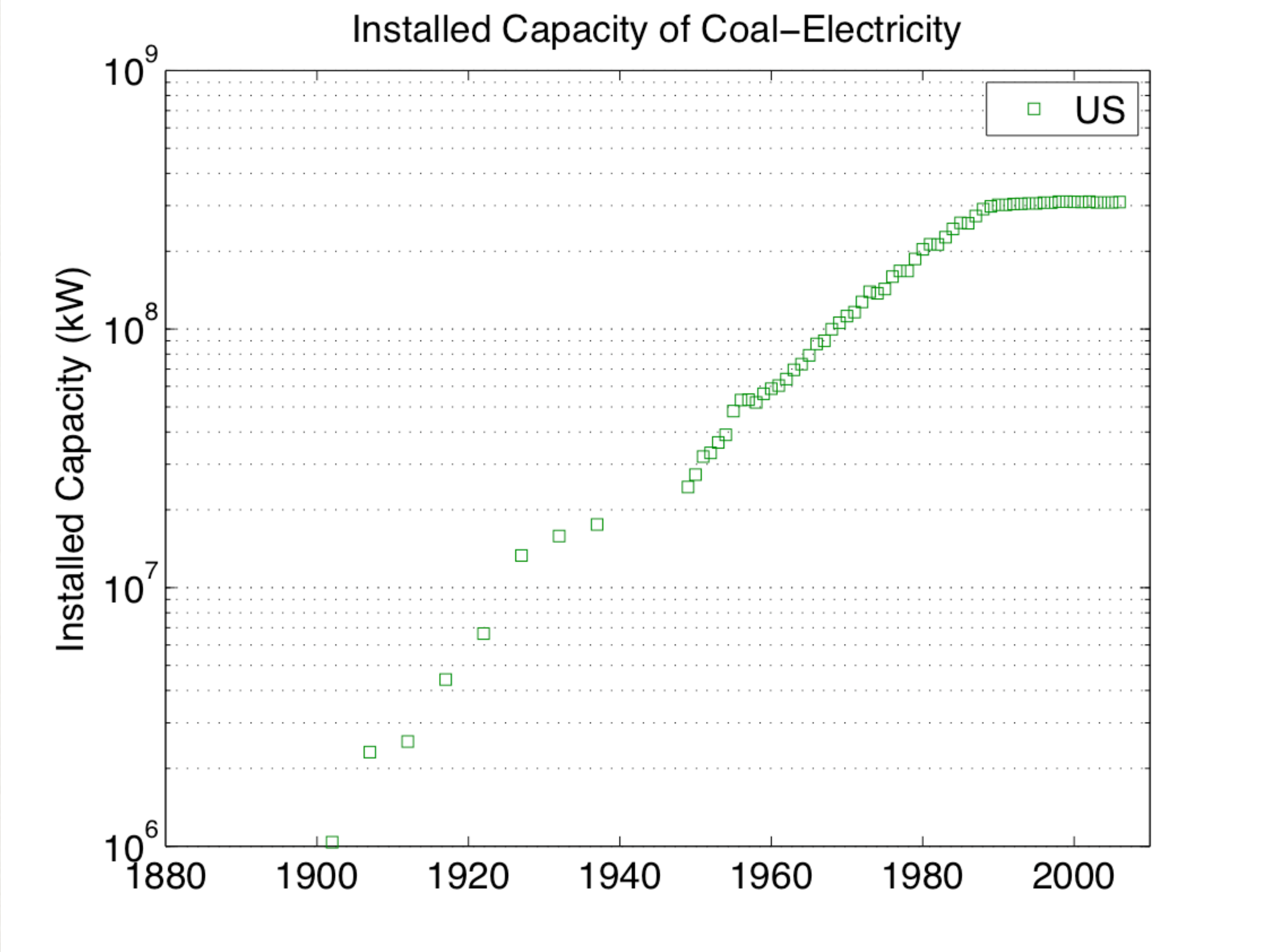
- Study on photovoltaics by Nemet showed that biggest factors driving improvement were decrease in material cost + increasing returns to scale. Is latter compatible with Wright's law?
- Assume perfect increasing returns, i.e. one a factor is built with cost C as many good as desired can be produced at no further cost.
- Cost per unit is C/n, where n is number of units.
- Trivial example of Wright's law with a = 1 (progress ratio = 0.5, which is too high).

Coal generated electricity

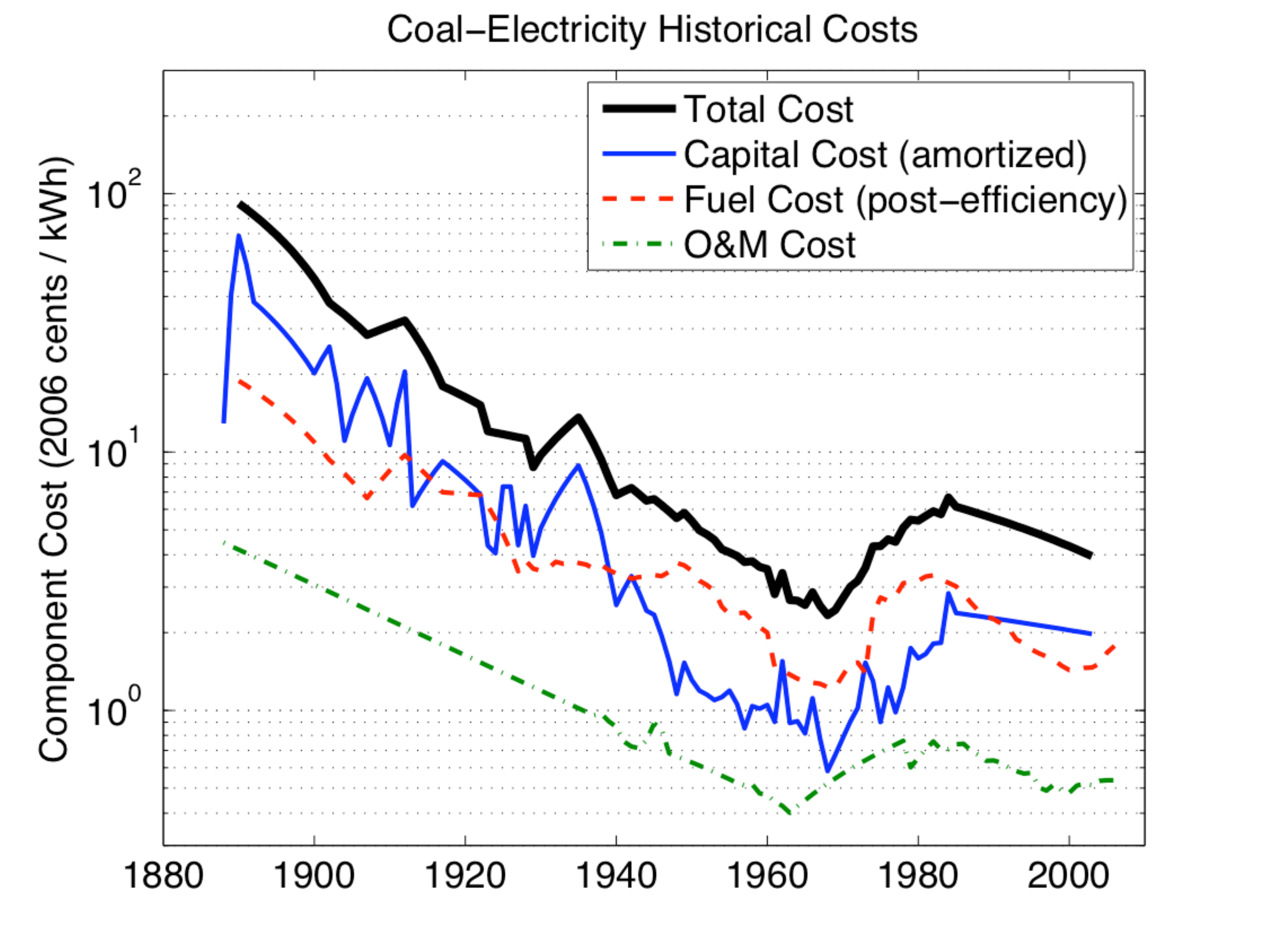
- What target do solar and other alternative technologies have to hit in order to break even with coal?

- Assume best case for coal: Carbon sequestration is free, no pollution controls.

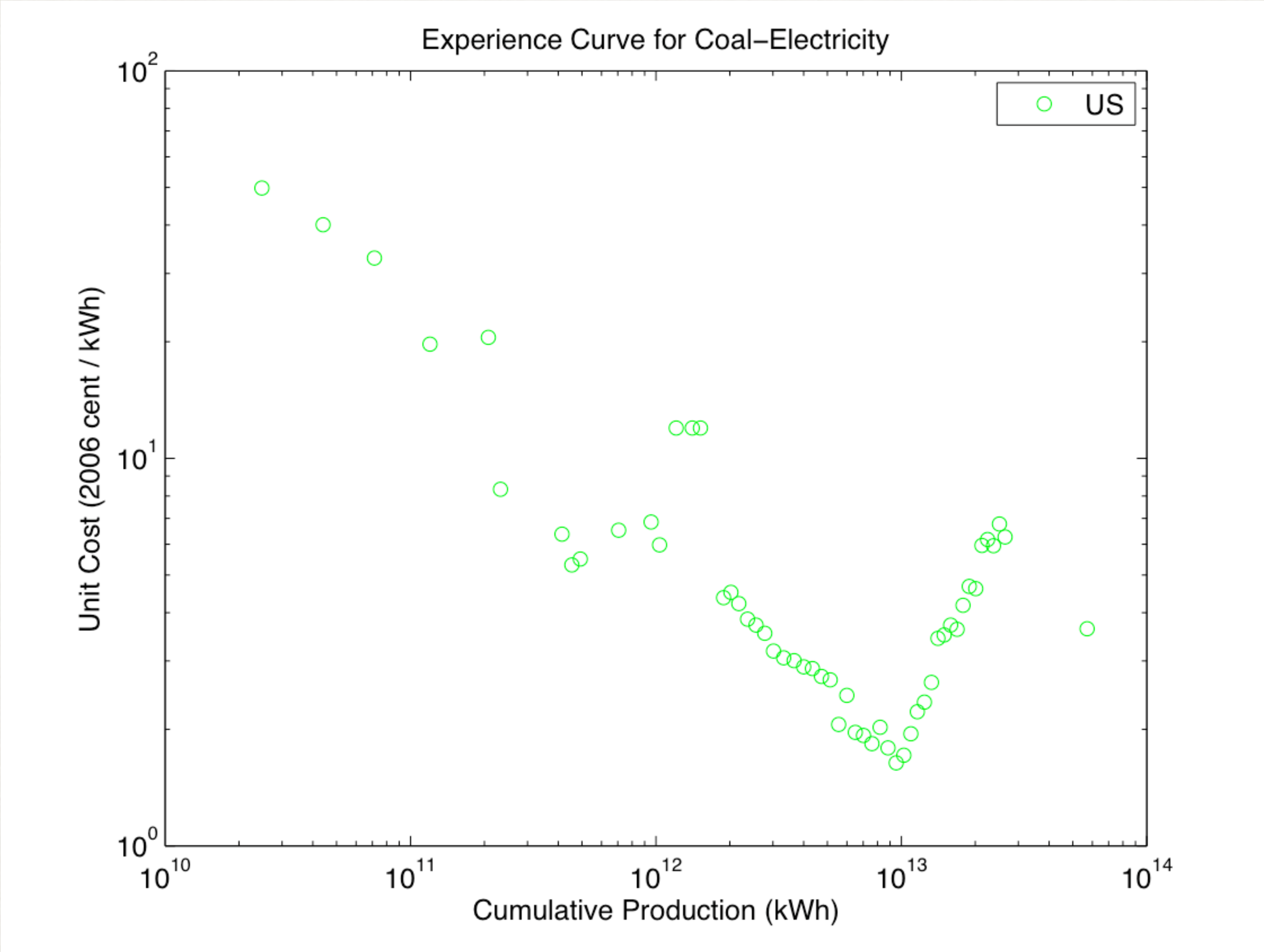
- What is the price of coal-generated electricity likely to do with time?



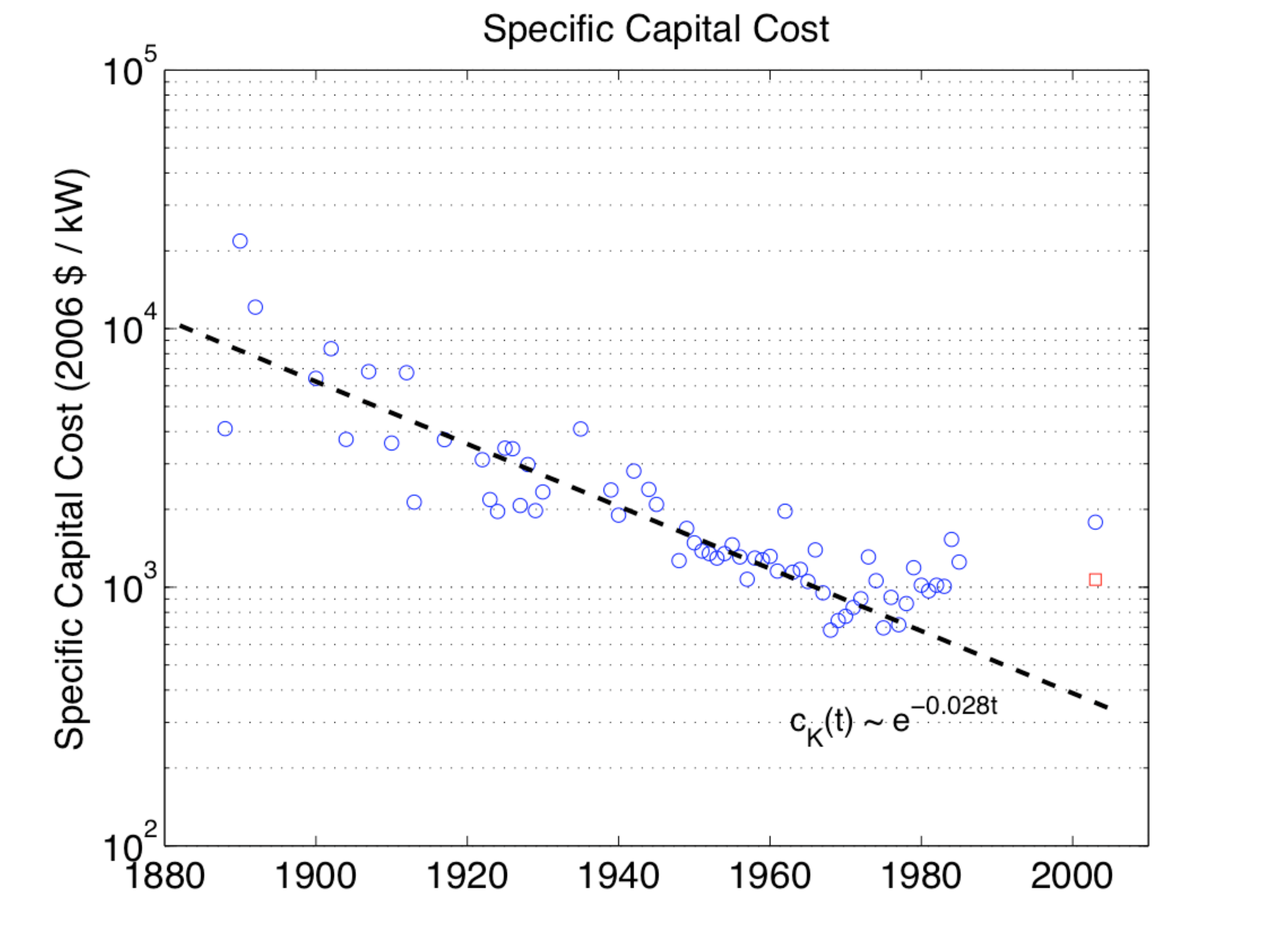
Installed Capacity of Coal–Electricity
Installed Capacity (kW)
10^9
10^8
10^7
10^6
1880
1900
1920
1940
1960
1980
2000
US



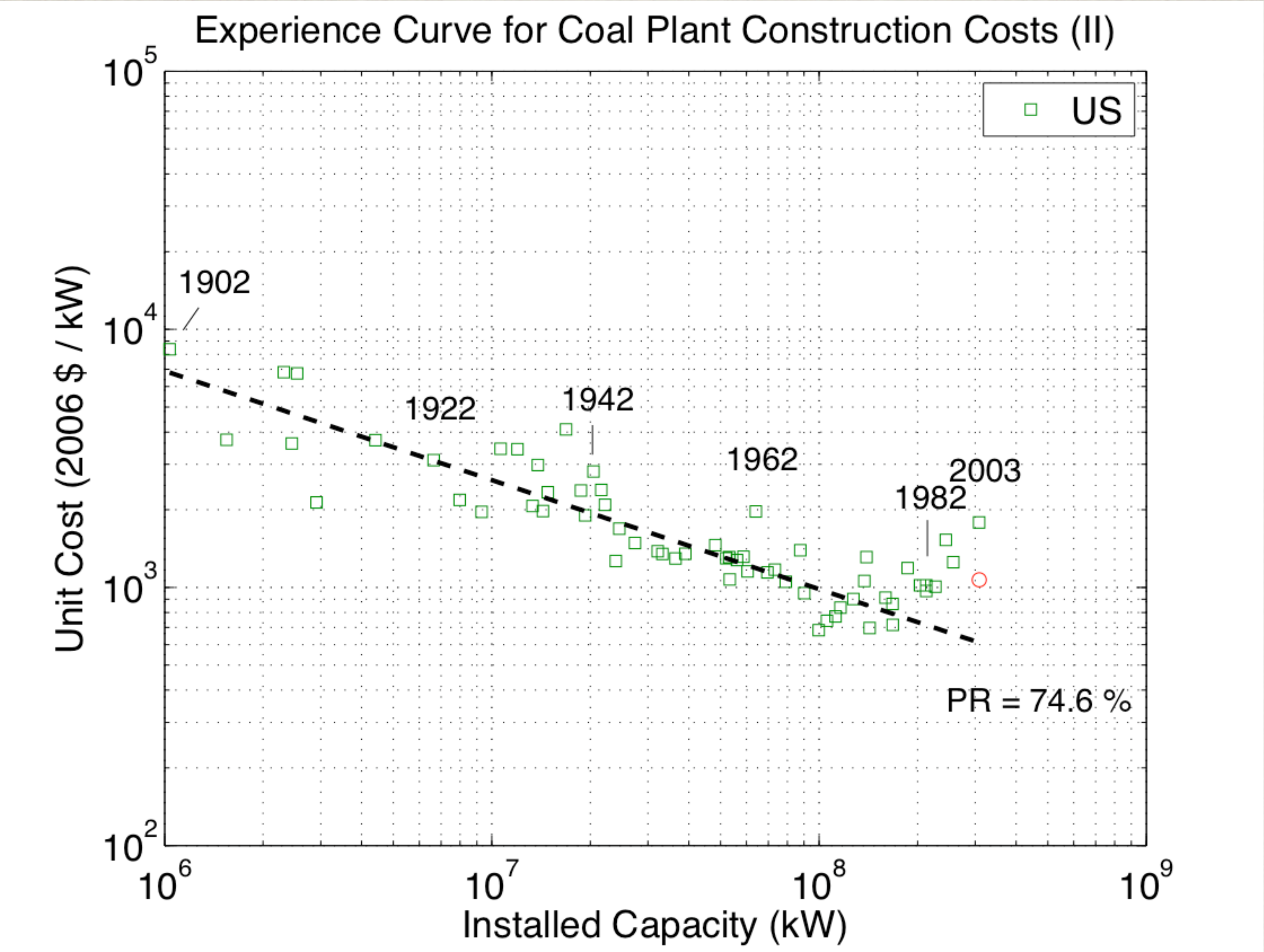
Coal–Electricity Historical Costs
Total Cost
Capital Cost (amortized)
Fuel Cost (post–efficiency)
O&M Cost
Component Cost (2006 cents / kWh)
10^2
10^1
10^0
1880
1900
1920
1940
1960
1980
2000



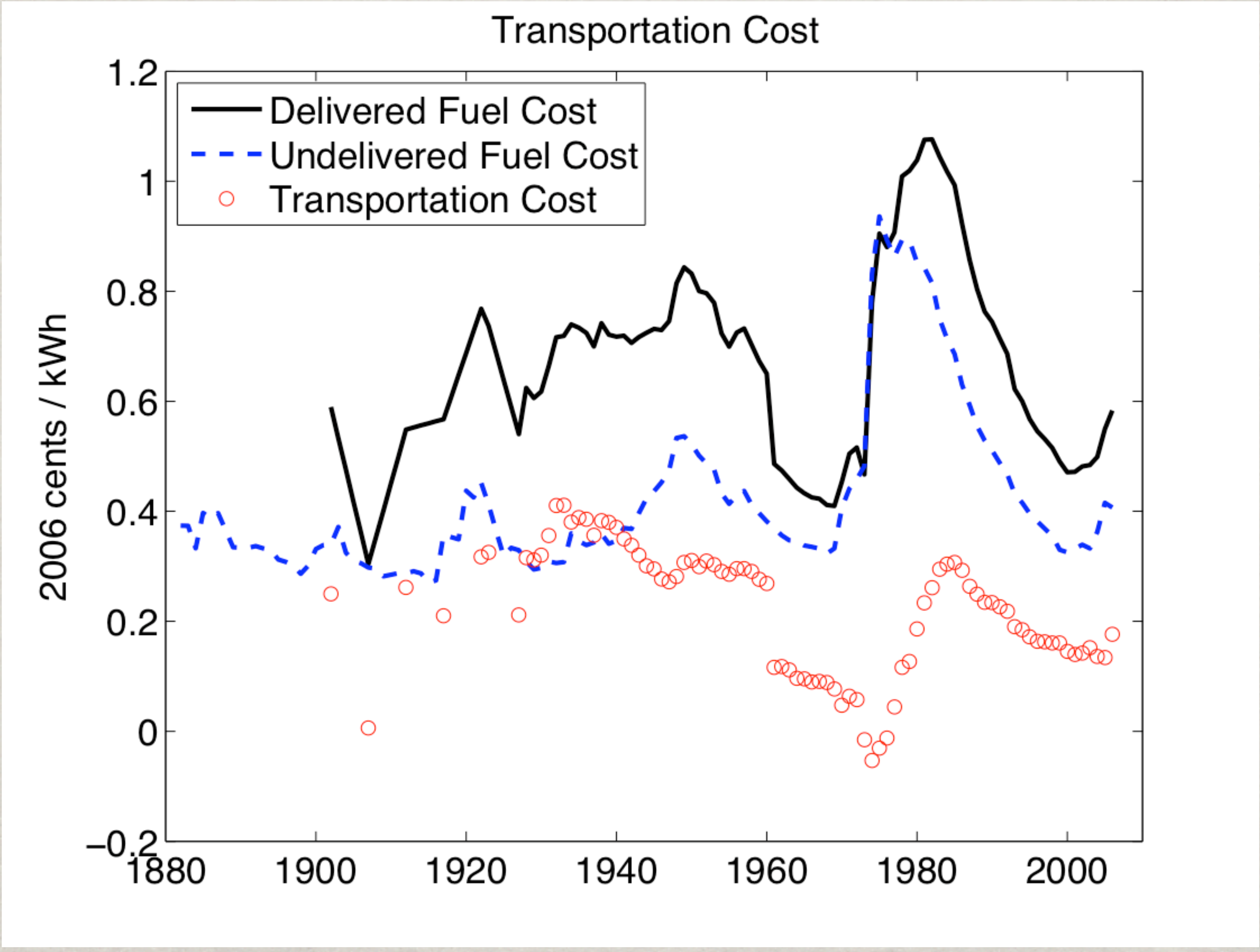
Experience Curve for Coal–Electricity
US
Unit Cost (2006 cent / kWh)
10^2
10^1
10^0
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}
Cumulative Production (kWh)



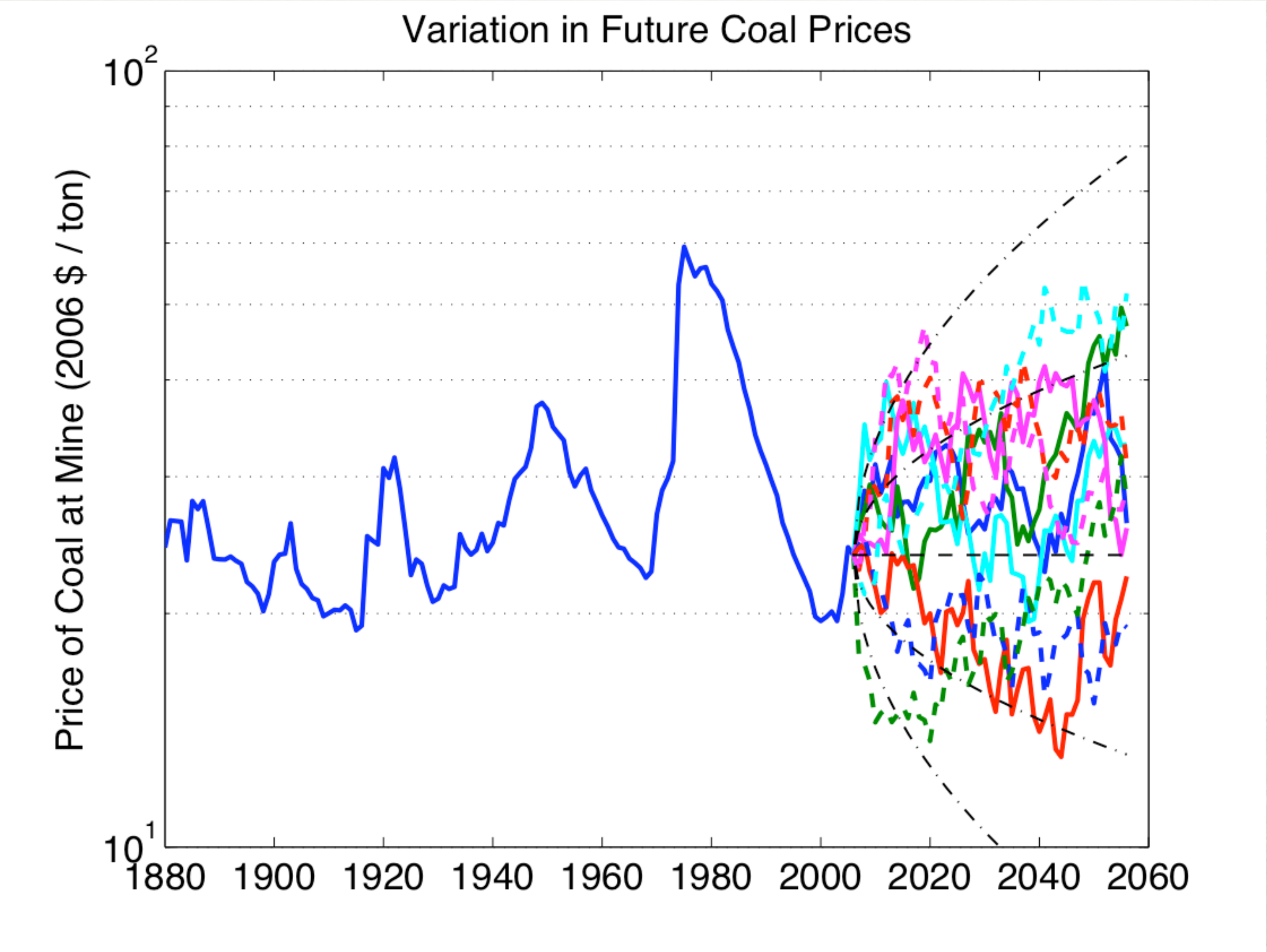
Specific Capital Cost
Specific Capital Cost (2006 $ / kW)
10^5
10^4
10^3
10^2
1880
1900
1920
1940
1960
1980
2000
$c_K(t) \sim e^{-0.028t}$



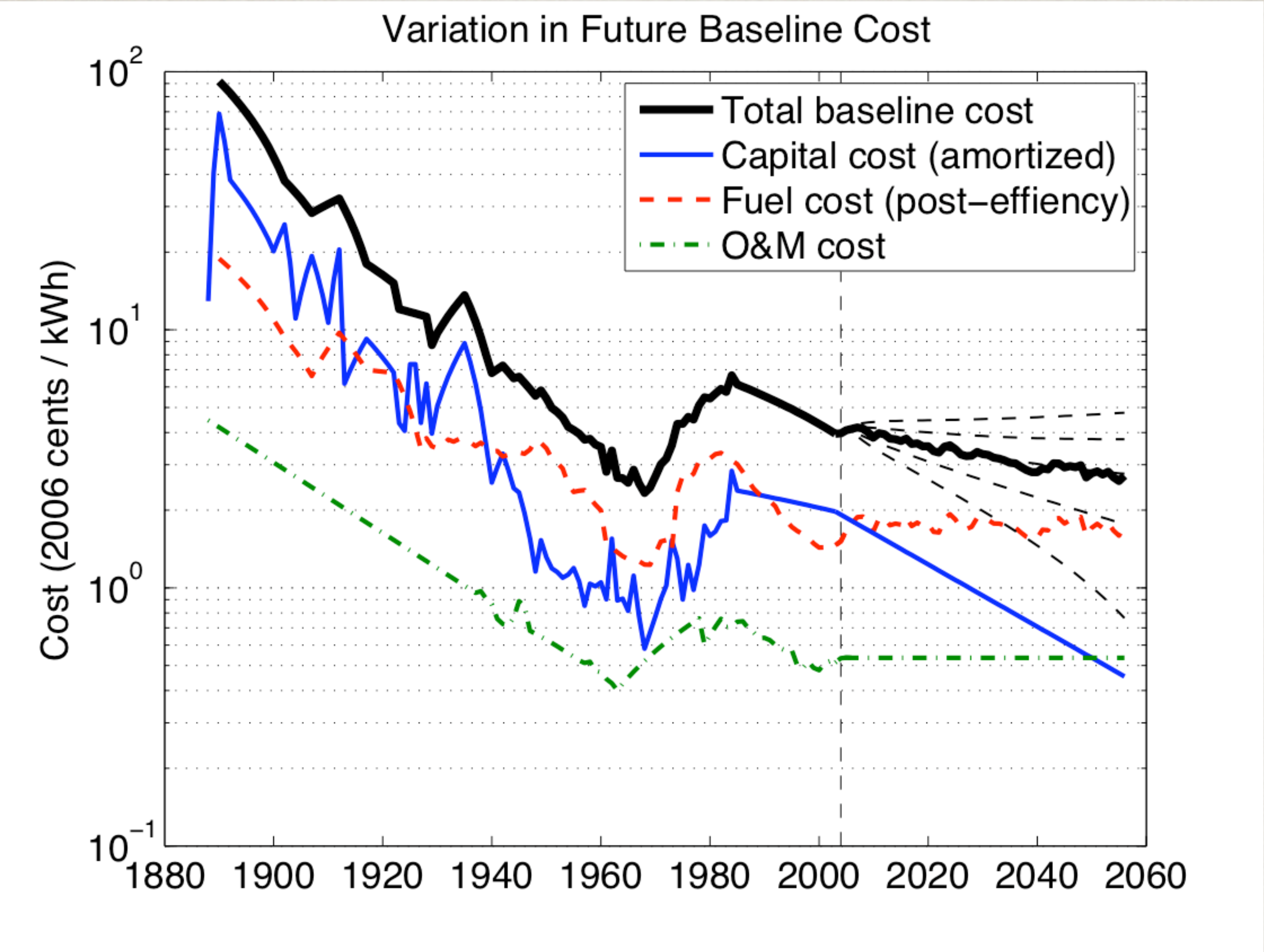
Experience Curve for Coal Plant Construction Costs (II)
US
1902
1922
1942
1962
1982
2003
PR = 74.6 %
Unit Cost (2006 $ / kW)
Installed Capacity (kW)
10^2
10^3
10^4
10^5
10^6
10^7
10^8
10^9

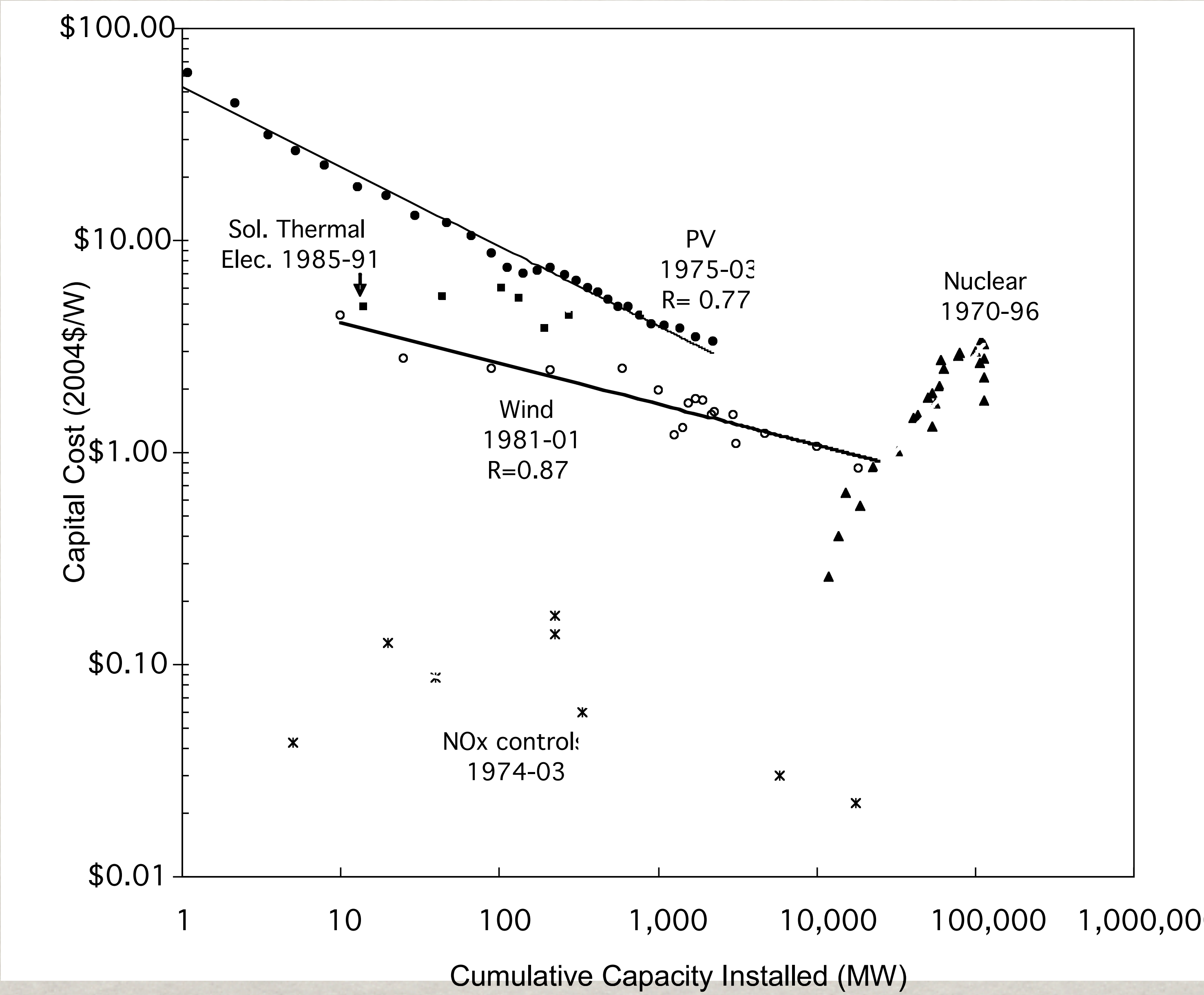


Transportation Cost
Delivered Fuel Cost
Undelivered Fuel Cost
Transportation Cost
2006 cents / kWh
1.2
1
0.8
0.6
0.4
0.2
0
−0.2
1880
1900
1920
1940
1960
1980
2000



Variation in Future Coal Prices
Price of Coal at Mine (2006 $ / ton)
10^2
10^1
1880
1900
1920
1940
1960
1980
2000
2020
2040
2060


Variation in Future Baseline Cost
Total baseline cost
Capital cost (amortized)
Fuel cost (post−effiency)
O&M cost
Cost (2006 cents / kWh)
10^2
10^1
10^0
10^−1
1880
1900
1920
1940
1960
1980
2000
2020
2040
2060



$100.00
$10.00
$1.00
$0.10
$0.01
Capital Cost (2004$/W)
Sol. Thermal
Elec. 1985-91
PV
1975-03
R= 0.77
Nuclear
1970-96
Wind
1981-01
R=0.87
NOx controls
1974-03
1
10
100
1,000
10,000
100,000
1,000,000
Cumulative Capacity Installed (MW)

Portfolio design

- Performance curves imply increasing returns
  - Risk of lock-in to an inferior technology
  - Assume functional form: $y=ax^{-b}$
  - If a and b are both diverse and uncertain, trade-off between diversification and concentration
  - Highly nonlinear stochastic dynamical system

Discounting the future

- How does one compare something today with something tomorrow?
- How do we value something for current generations in comparison with future generations?
- Ramsay (1928): For consumption stream $(C_1, C_2, \ldots)$

$$V = U(C_1)D_1 + U(C_2)D_2 + \ldots$$

- Ramsay argued for $D_t = 1$
  - To discount later generations in favor of earlier ones is "ethically indefensible and arises merely from the weakness of the imagination"

Exponential discounting

- Standard approach in neoclassical economics is exponential discounting (Samuelson).

$$D_\tau = \beta^{-\tau} = e^{-r\tau}$$

- E.g. can be justified by opportunity cost. A dollar in the bank grows with interest rate r.
  - At time τ you would have $e^{r\tau} > 1$
  - Discount for time τ is therefore

$$\frac{\text{money now}}{\text{money later}} = e^{-r\tau}$$

Time consistency

- Exponential discounting is time consistent, I.e.

$$\frac{U(C,t,\tau)}{U(C,t,\tau')} = \beta^{\tau-\tau'}$$

independent of t.

- Exponential discounting is the only time consistent discounting function
- Time consistency is not necessarily rational.

Value of far future under exponential discounting?

- Under exponential discounting with realistic interest rates, the far future is not worth much
- E.g., with interest rate of 6%, 100 years out the discount factor is 0.0025.
- This is used by some economists to argue that we should put very little effort into coping with phenomena such as global warming that create problems in the far future.

Copenhagen Consensus

(eight leading economists, four Nobel prize winners)

Bjorn Lomborg

Concerning global warming: "If we use a large discount rate, they will be judged to be small effects" (Robert Mendolson, criticizing an analysis by Cline using 1.5% discounting)

Discounting of far future is very sensitive to the interest rate

100 years into the future:

interest rate	10%	5%	1%
discount factor	5×10^{-5}	7×10^{-3}	0.37

Interest rates vary

Hyperbolic discounting

- People are not time consistent
- The effective interest rate is a decreasing function of t.
- The most commonly used functional form with this property is

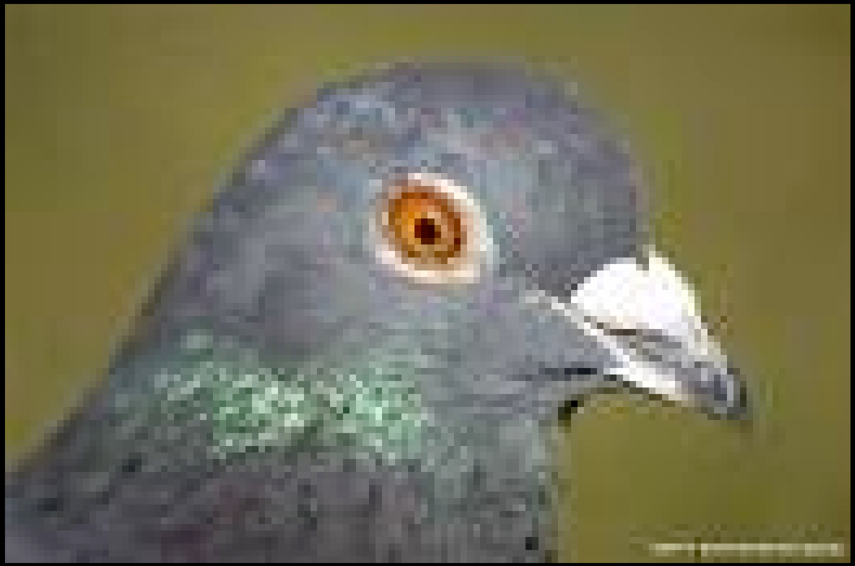
$$D(t) = (1 + \alpha t)^{-\beta}$$

E.g. Thaler experiment

- How much money would you need in the future in lieu of $15 today?

time	amount	discount	interest rate
month	$20	$\mathrm{D}(1) = \frac{15}{20} = 0.75^{1}$	345%
year	$50	$D(12) = \frac{15}{50} = 0.90^{12}$	120%
10 years	$100	$D(120) = \frac{15}{100} = 0.98^{120}$	19%

Even animals use hyperbolic discounting



Widely viewed as “irrational”, or at least “behavioral”.

The world is not constant

- Rewards vary
- Hazards vary
- Interest rates vary
- The future is uncertain, and uncertainties are typically correlated in time.
- Under these circumstances, on average hyperbolic discounting is rational -- each step uses exponential discounting, but at varying rates. Result is not exponential!

Discounting under uncertainty

- If interest rate r is uncertain, “certainty equivalent” discount factor is

$$\text{average}[D(t)] = \text{average}[\exp(-\sum_{i=1}^{t} r_t)]$$

- Average discount factors, not interest rates: small rates dominate at long times.
  - (Weitzmann, 1998) uncertainty about fixed interest rate
  - (Axtell, 2006) uncertainity about subjective discount rate.
  - (Newell and Pizer, 2003) fluctuating rates
- Must model interest rate process

Binomial random walk interest rate model

Define recursively. Let $x(t)$ be valuation at time t, $r(t)$ interest rate.

$$x(t) = (1 + r(t-1))x(t-1)$$

$$r(t) = \begin{pmatrix} 1+\epsilon \\ 1/(1+\epsilon) \end{pmatrix} r(t-1)$$

with equal probability for an increase or decrease. Assume an asset of known value in future, and work backward to find present value.

I.e., use current interest rate at each step; increase or decrease interest rate at next time by randomly multiplying or dividing current interest rate by a factor greater than one.

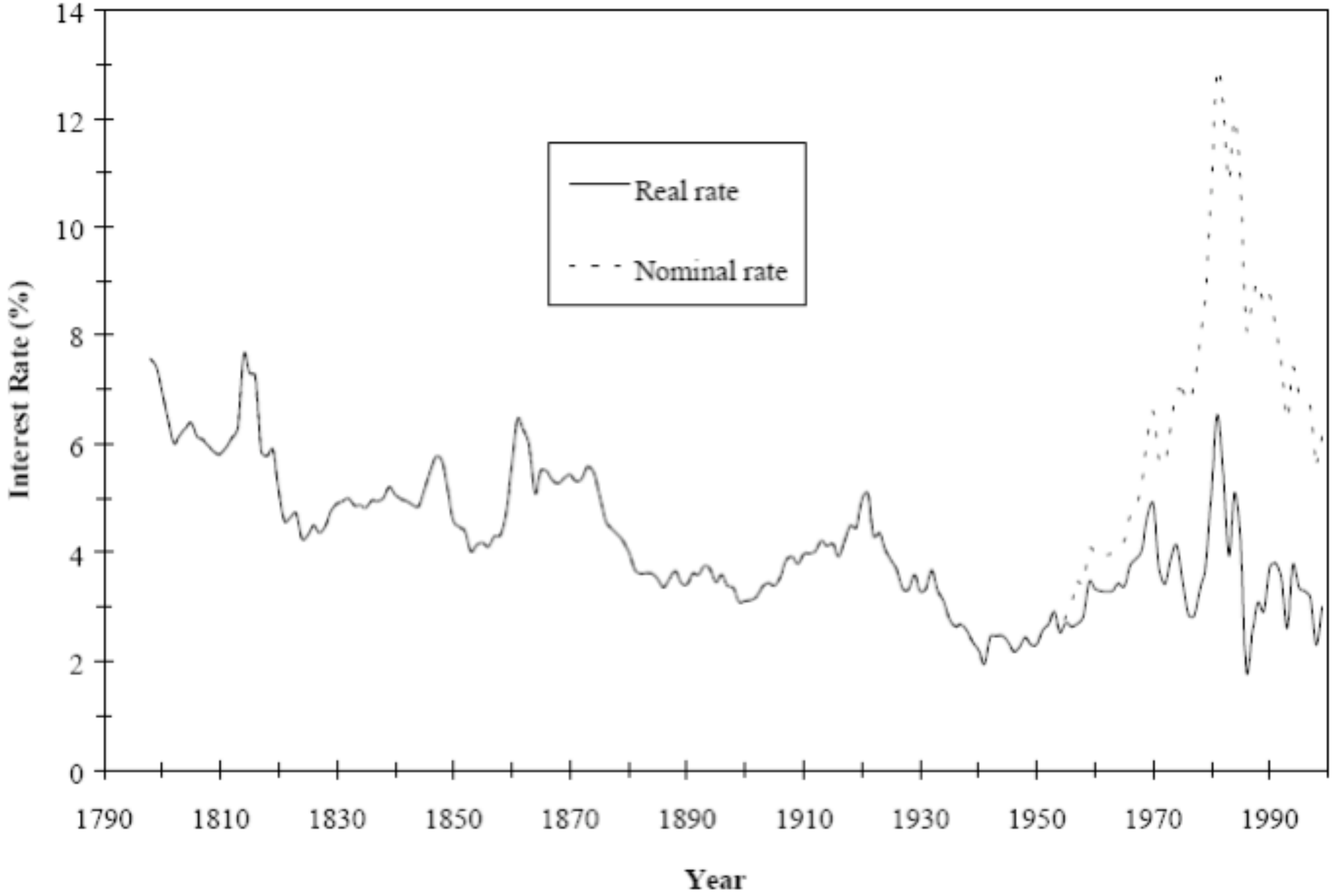
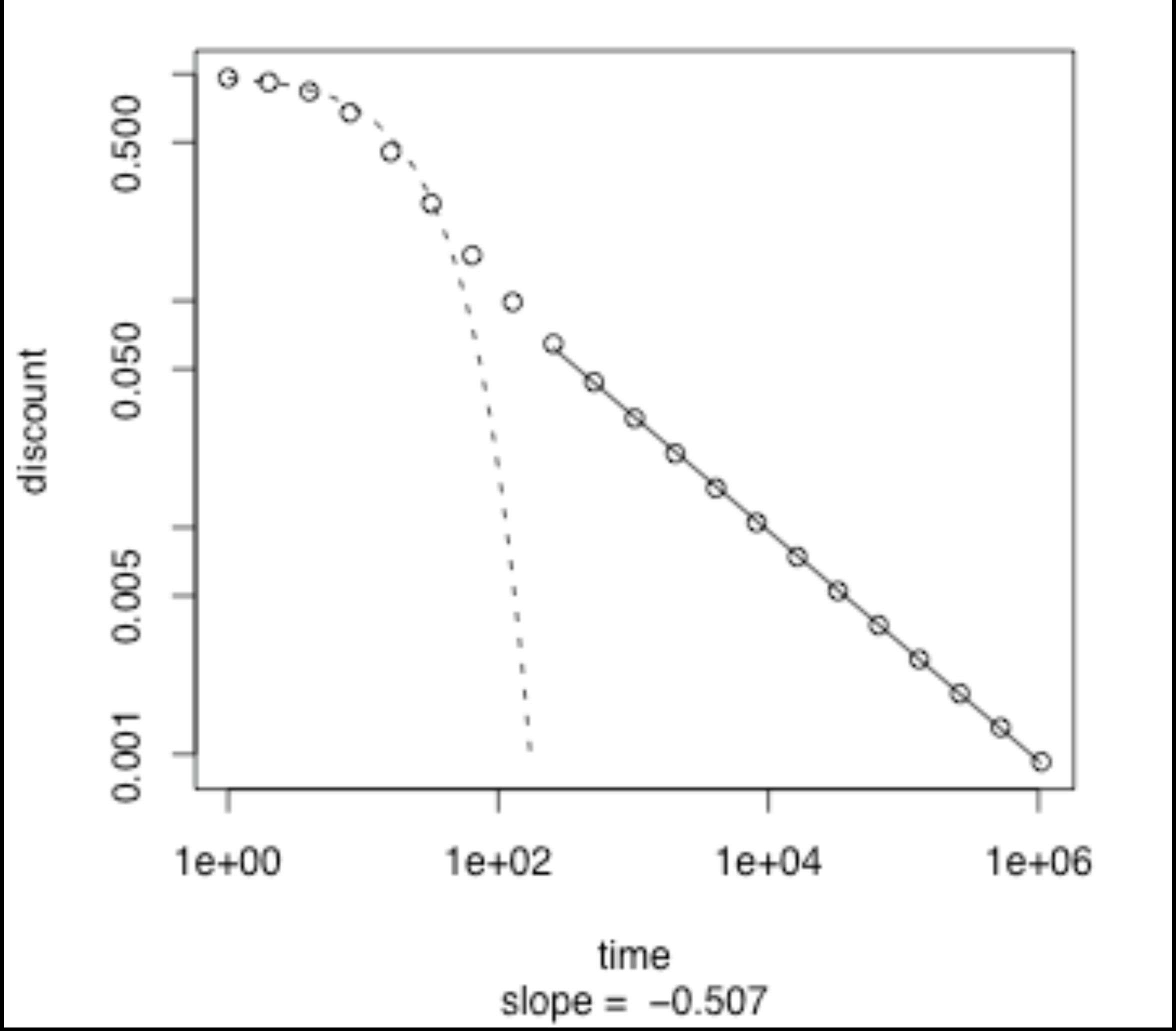


Figure 2. Market Interest Rate on U.S. Long-Term Government Bonds (1798–1999)

Comparison of discount functions (15% annual volatility, 4% initial rate)

year	rnd. wlk.	constant
20	46.2	45.6
60	12.5	9.5
100	5.1	2.0
500	0.80	2×10^{-7}
1000	0.50	4×10^{-16}

r0=4%, v = 50%



Farmer and Geanakoplos

Theoretical explanation

- Consider high volatility limit
- Discount rate tree has a "cliff": 0 or 1
- Discount rate is fraction of paths that do not cross the cliff.
- Random walk with barrier crossing
- Scales as $t^{-1/2}$
- Implies non-integrability!

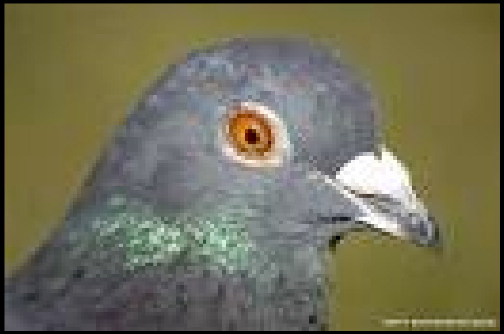
Values vs. science

- In economic analyses, it is important to distinguish which conclusions come from values, which from science.
- Typical economics model assumes maximizing utility (monetary wealth) for present generations only (and people only).
  - Utility for as yet unborn children?
  - Utility for environment?

Iroquois constitution

- Gayanashagowa -- Great Law of Peace -- constitution of the Haudenosaunee
- In every deliberation we must consider the impact on the 7th generation … even if it requires having skin as thick as the bark of a pine.

Who is the better economist?



pigeon

12 economists in
Copenhagen consensus

Conclusions

- When planning for the future, it is rational to discount the future at a rate that decreases with time horizon (e.g. power law, not exponential).
- Whether we should do this depends on value judgment (how much do we care about our children, other species, …).
- We can use quantitative methods to improve forecasts of performance trajectories of future technologies. Need better studies to determine how well this can be done.
- With these elements, we should be able to construct better technology investment portfolios.

r0={.5, 1,100}%, v = 100%