

Scaling Dynamics in Energy Technologies

Historical Evidence & Implications

Charlie Wilson

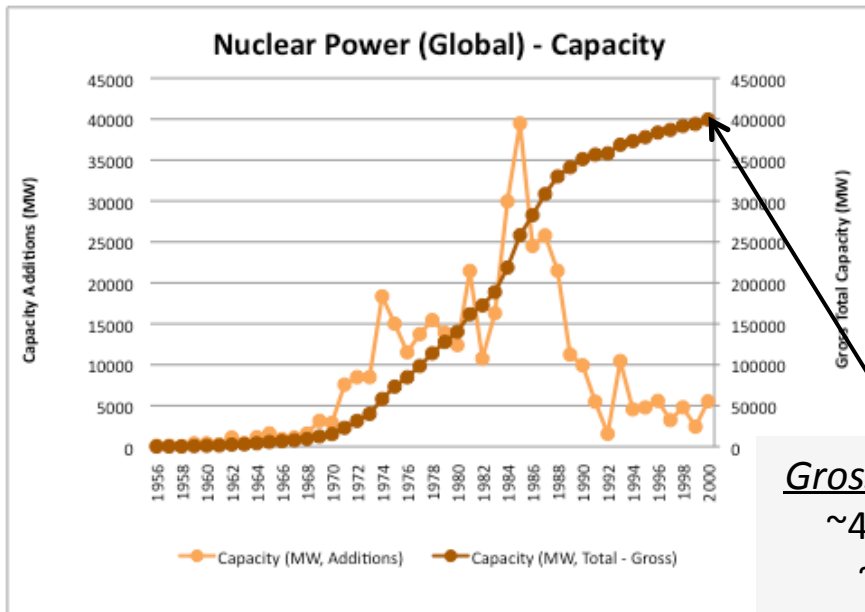
IIASA (International Institute for Applied Systems Analysis)

Presentation to Harvard ETIP

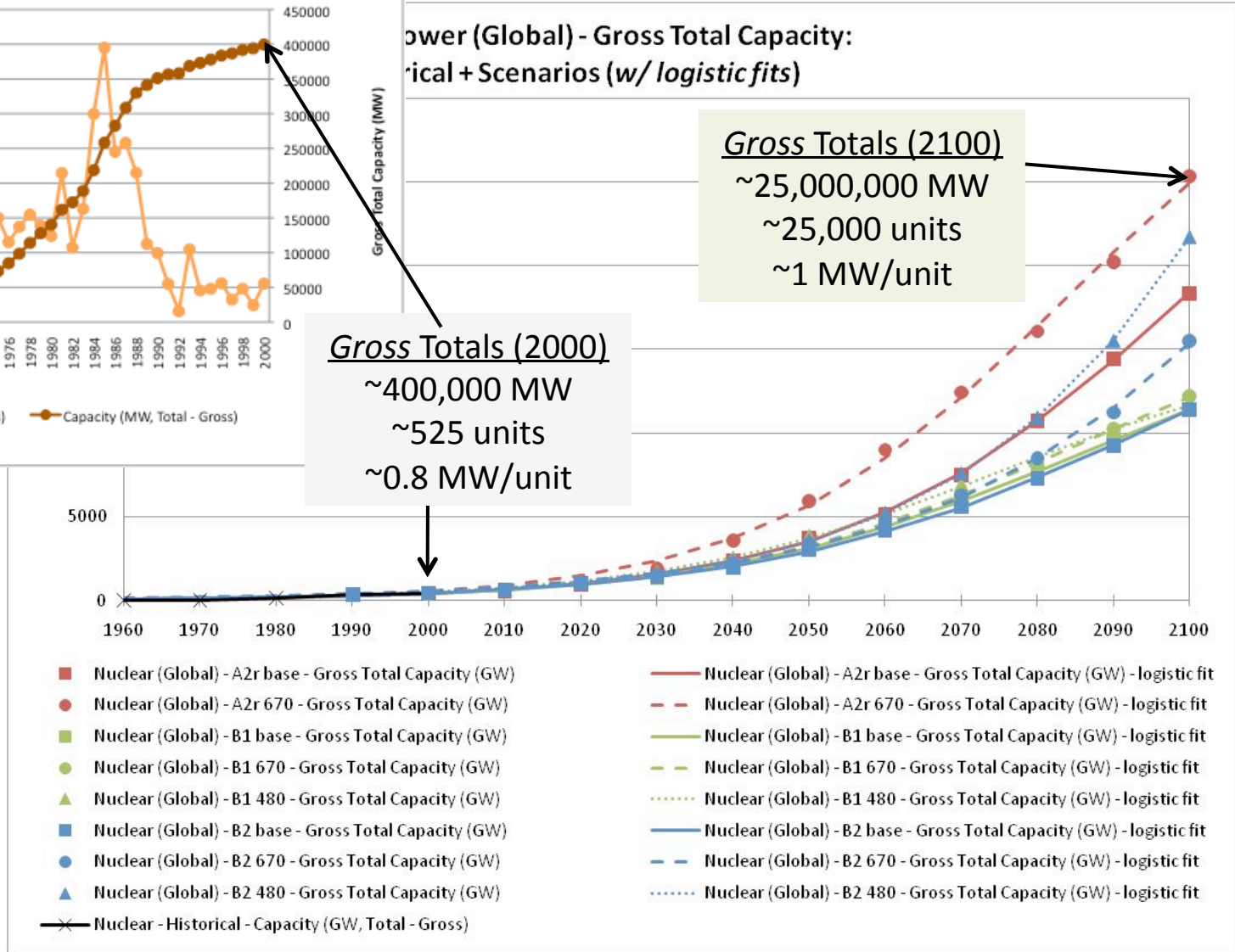
April 2009

For further details: wilsonch@iiasa.ac.at

Industry scaling: e.g., nuclear power



Nuclear Power (Global) - Gross Total Capacity:
Historical + Scenarios (w/ logistic fits)



Unit scaling e.g., wind power

power \approx blade length 2
wind speed 3



Product/Rotor diameter (m)	V15	V17	V19	V20	V25	V27	V39	V44	V47	V52	V66	V80	V90
Year of installation	1981	1984	1986	1987	1988	1989	1991	1995	1997	2000	1999	2000	2002
Capacity (kW)	55	75	90	100	200	225	500	600	660	850	1750	2000	3000
MWh/year	217	265	301	346	481	647	1304	1581	1947	2530	4705	6768	9152

Research Outline

(1) Definition of Scaling

Technological growth that is:

- (i) both rapid *and* extensive
- (ii) occurs at multiple levels:
 - the technology unit (&/or plant)
 - the industry as a whole

(2) Research Question

What are the historical dynamics of unit scaling and industry scaling for different energy technologies?

(3) Methodological Issues for a Technology Meta-Analysis

Technology diffusion changes over time

Technology diffusion changes over space

Variables of interest are rates *and* extents

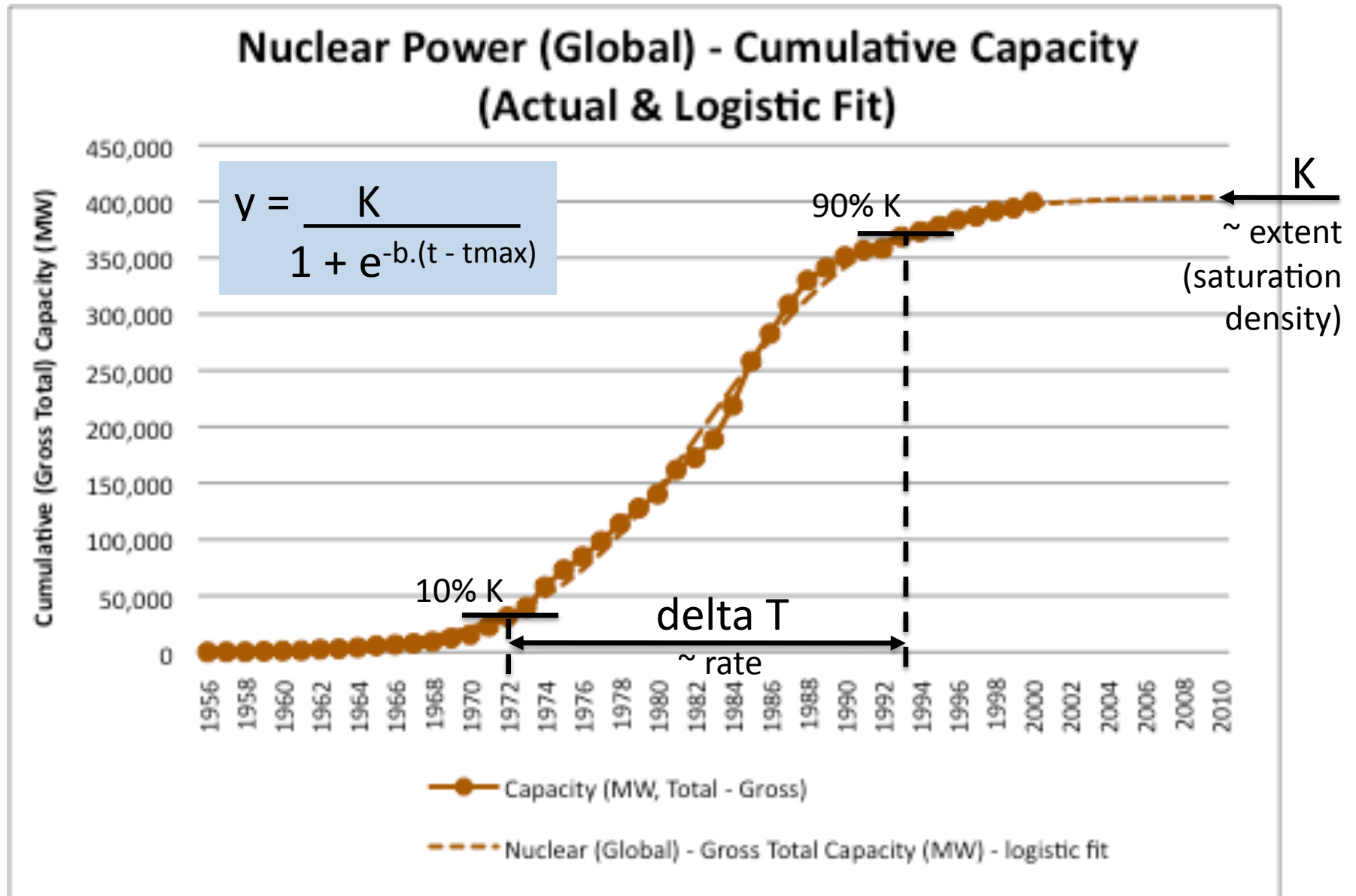
'Levels' of interest are unit *and* industry

Technological 'capacity' has specific units

-- > Use logistic parameters (delta T & K) to compare scaling dynamics across technologies *and* levels.

-- > Use MW as common capacity metric

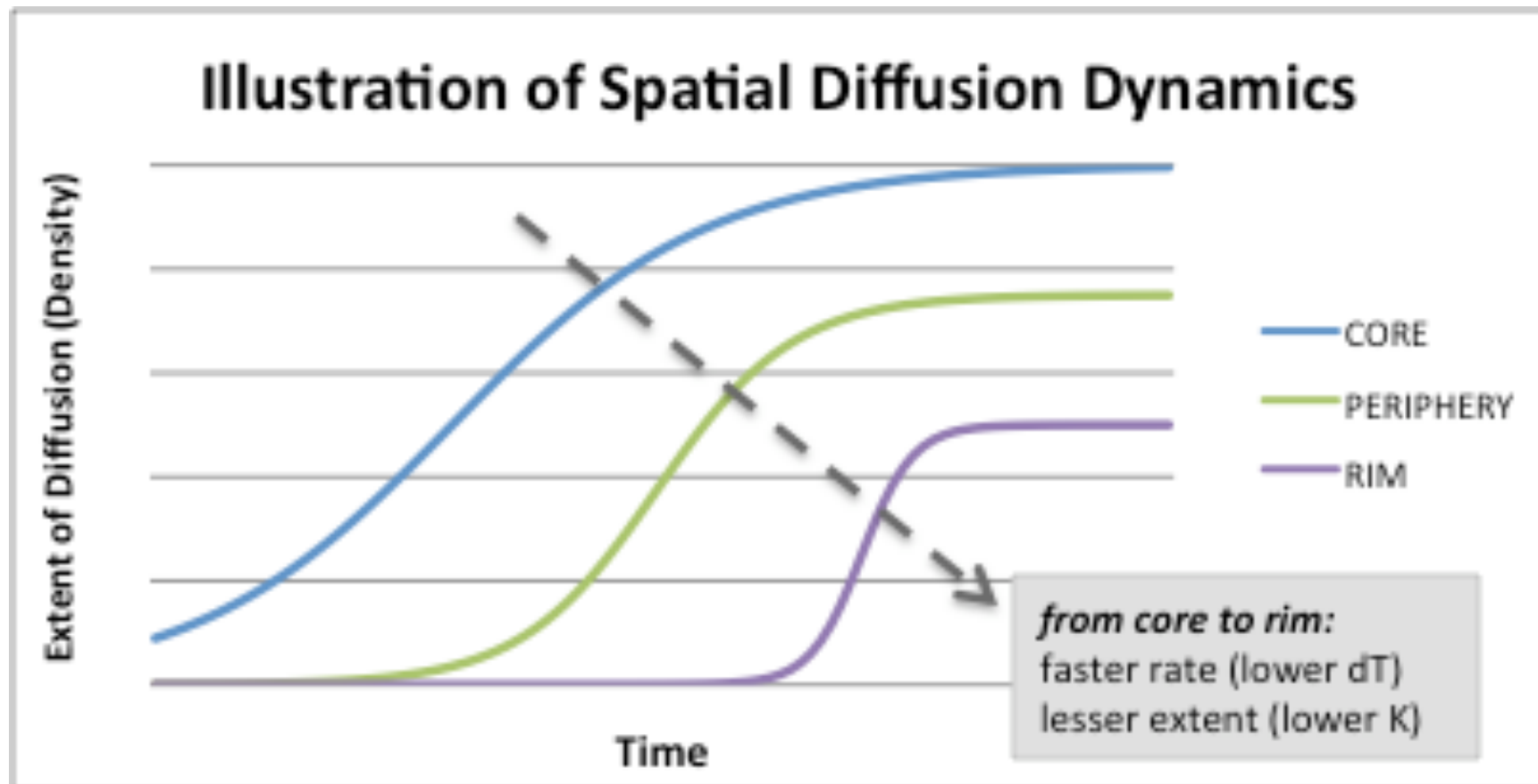
Key Logistic Parameters



Diffusion dynamics change from core to rim

“... acceleration of diffusion speed [ΔT] and decrease in ultimate diffusion levels [K] as a function of the ‘learning time’ [from the beginning of the diffusion process]”

(Grübler 1990)



Available Historical Data

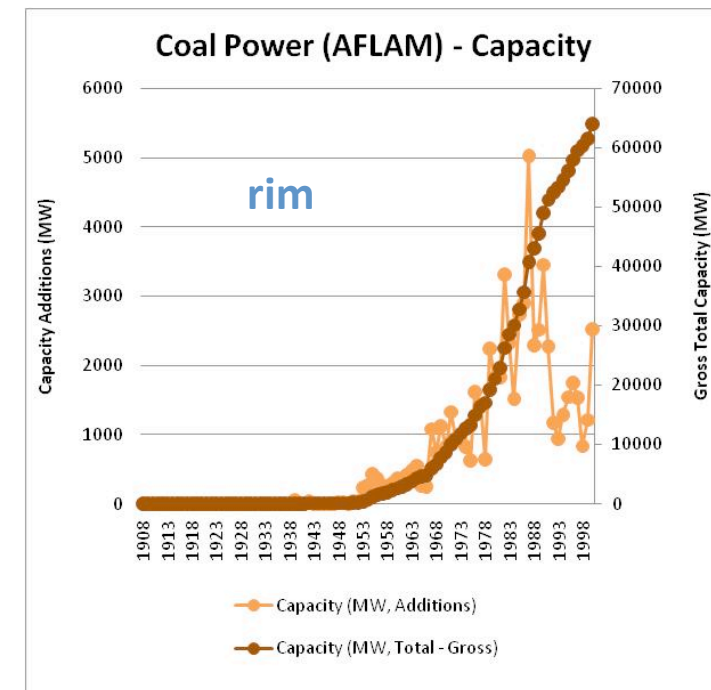
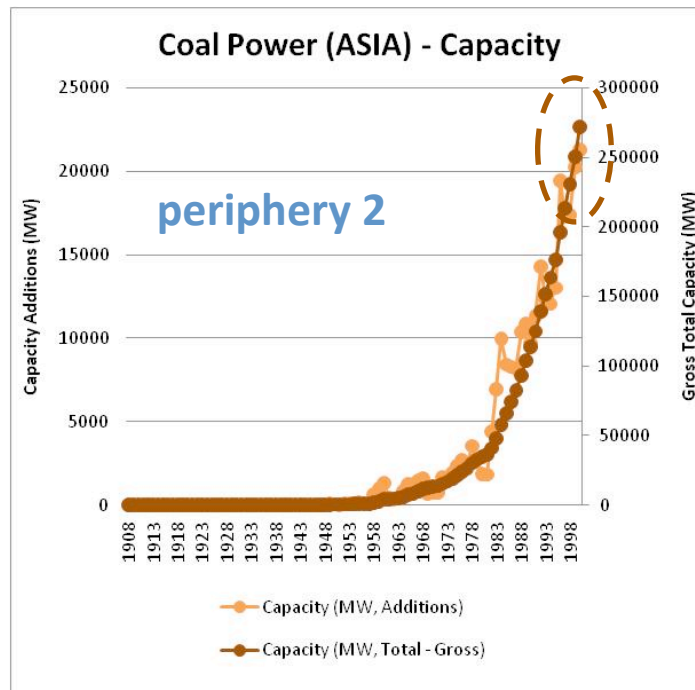
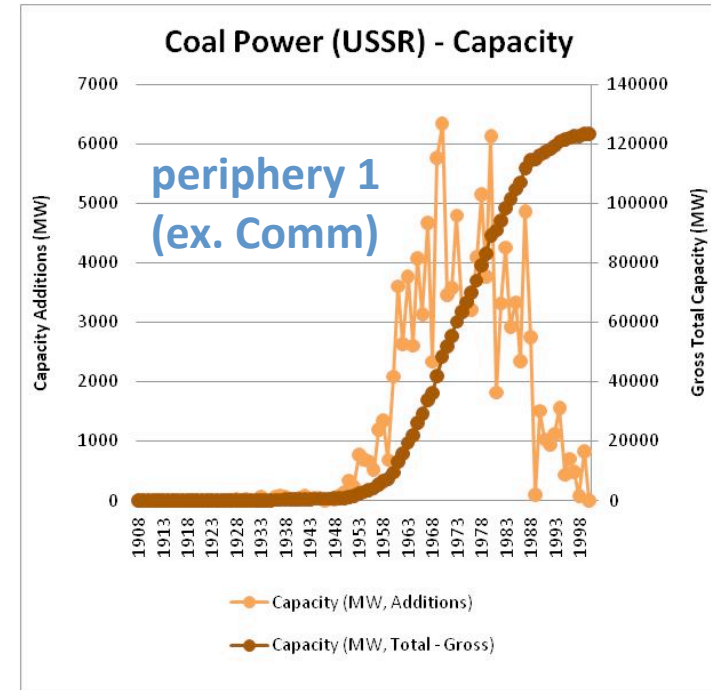
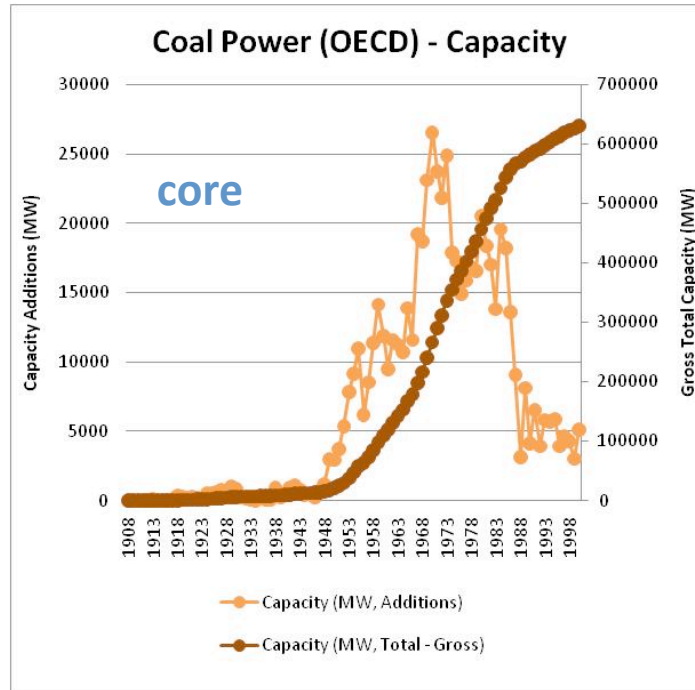
	Global	Core	Periphery 1 (ex. Comm)	Periphery 2	Rim	Notes
Power – Nuclear	✓	✓	✓	✓	✓	Installed capacity data
Power – Coal	✓	✓	✓	✓	✓	Installed capacity data
Power – Gas	✓	✓	✓	✓	✓	Installed capacity data
Power – Wind	✗	✓	✗	✗	✗	Denmark as core market
Refineries	(✓)	(✓)	(✓)	(✓)	(✓)	Processing capacity data
Jet Aircraft	(✓)	(✓) Boeing only	✗ <i>(Iljushin, Tupolev ...)</i>	(✓) Airbus only	✗	Boeing, McD, Airbus only
Motor Vehicles	(✓)	✓	(✓)	(✓)	(✓)	Production not use data
CFLs	✗	(✓)	✗	✗	✗	Sales not use data

Also: **Prime Movers** (US only); **Helicopters** (Unit Scale only)

Insufficient Time Series Data: **Solar PV**; **Mobile Phones**.

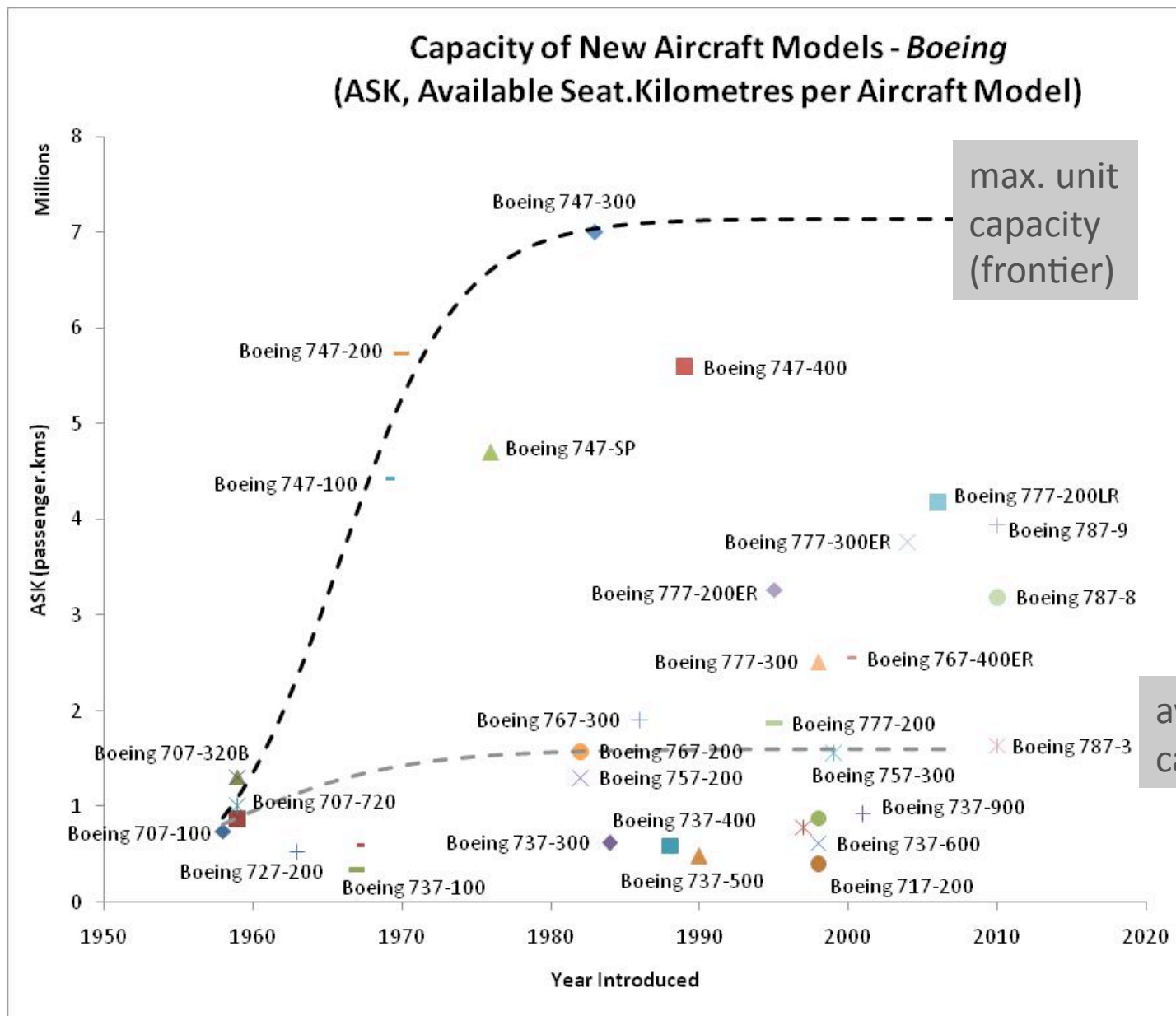
Industry
Capacity
Scaling

Coal Power
Generation:
Capacity
Additions &
Gross Totals



(N.B.
Same timescale,
different
y-axis)

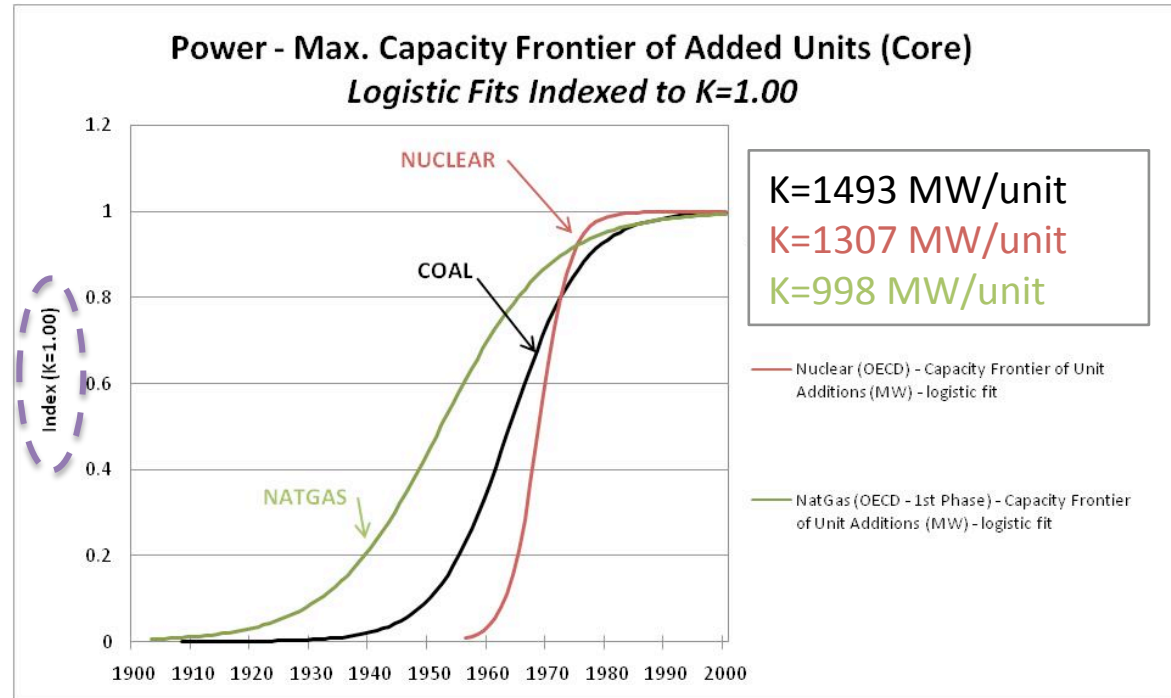
Unit Capacity Scaling: New Jet Aircraft Models (Boeing)



UNIT SCALE ECONOMIES

Rate of scaling of max. unit capacity

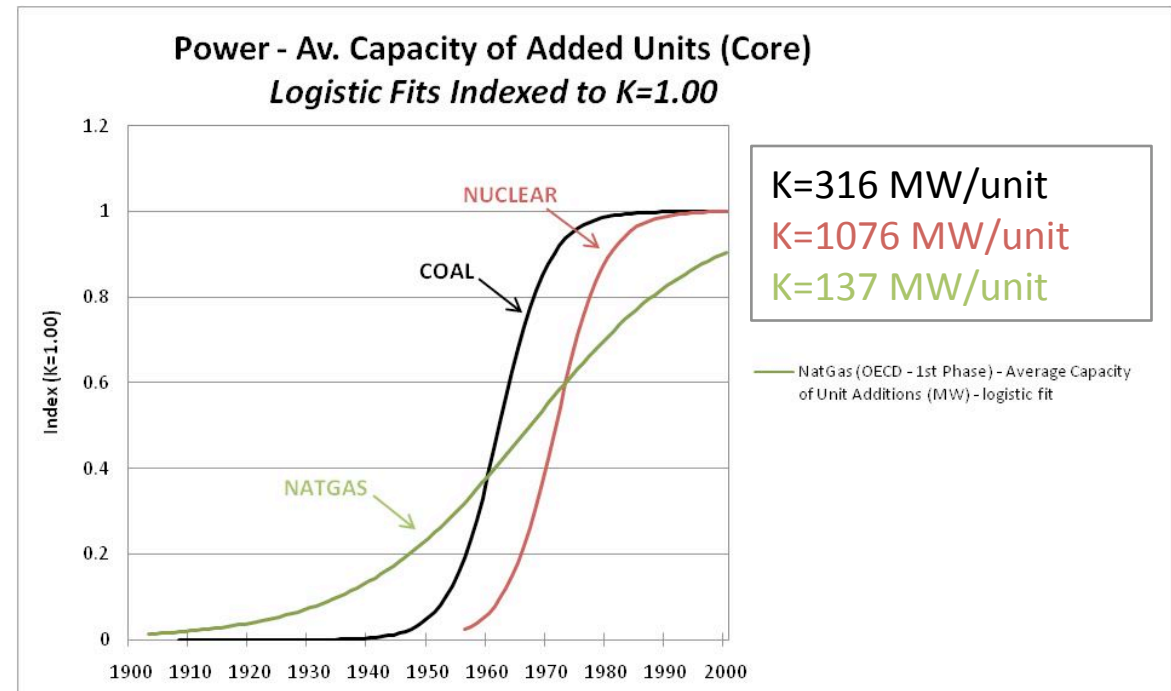
nuclear > coal > gas



UNIT SCALE FLEXIBILITY

Max. – average rate of unit scaling

gas >> coal > nuclear



Key Findings:

Historical patterns of scaling in energy technologies

- Industry scaling is initiated *and* sustained by more unit numbers not larger unit sizes.
- Unit scale economies, if available, tend to be captured early.
- Unit scale economies do not diffuse spatially from core to rim markets.

... Implications for Technology Policy

- The relationship between the rate and extent of industry scaling is consistent across technologies, and over time.

... Implications for Low Carbon Scenarios

If unit scale economies are available, unit scaling is faster than industry scaling



dT: Maximum unit capacity

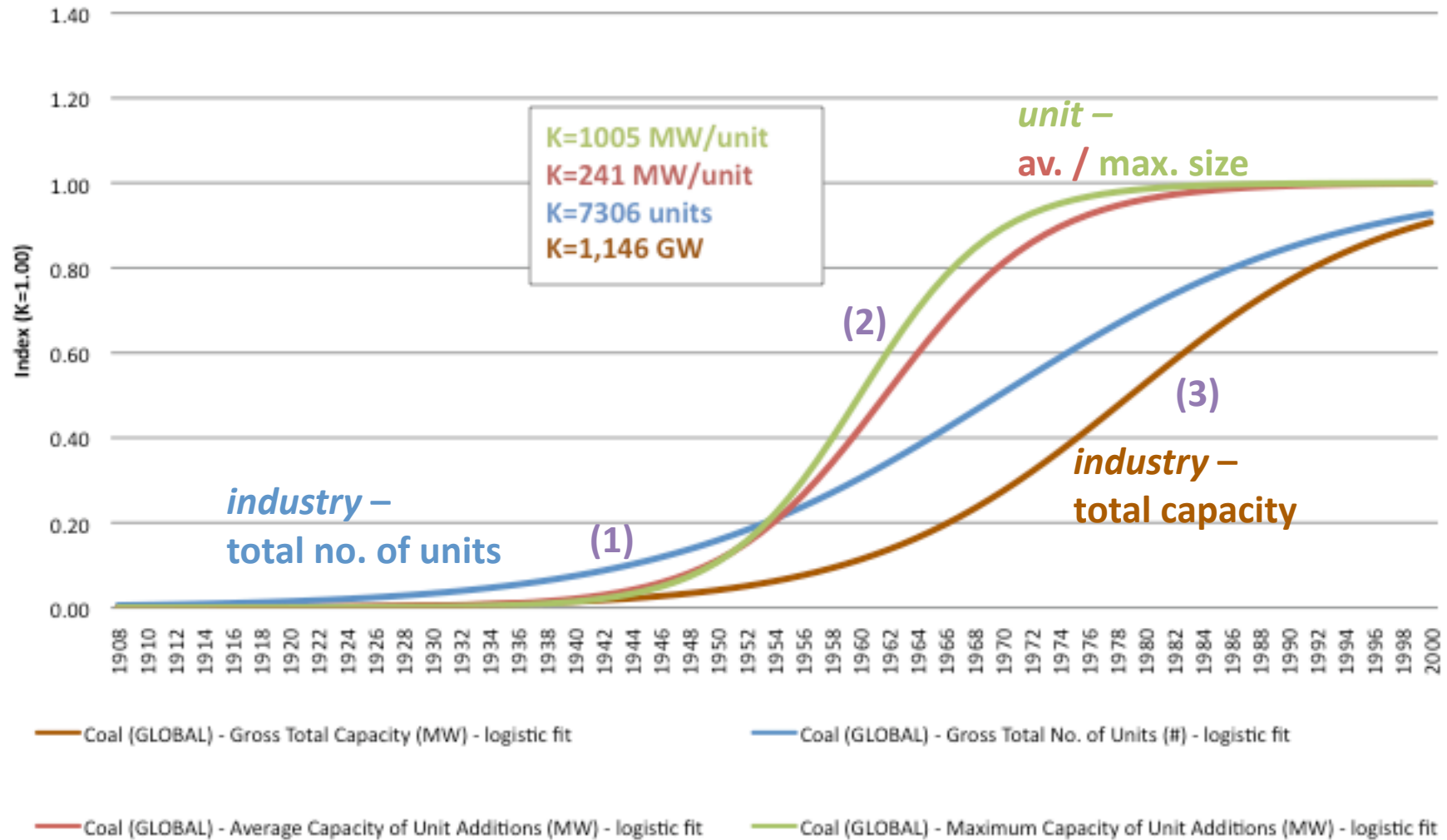
dT: Average unit capacity

dT: Total industry capacity

unit scale economies

scale invariant

Coal Power (Global) - Logistic Growth at Different Scales



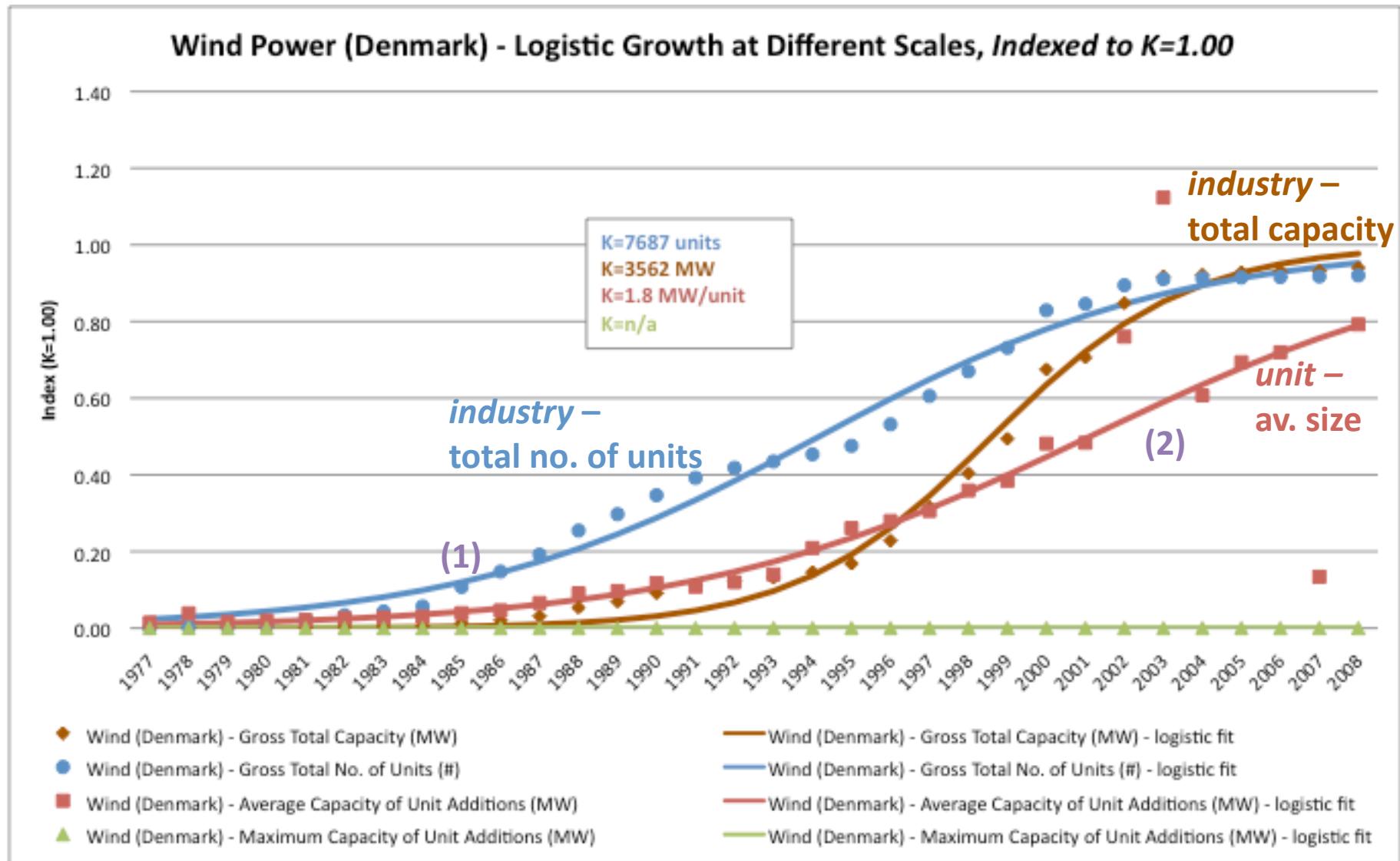
(1) Initial growth in unit numbers – experimentation!

(2) Unit scaling (max. & average, i.e., capturing scale economies)

(3) Industry scaling sustained by unit numbers

cf. nuclear, gas, aircraft, cars

Wind Power – Denmark (Core Market)

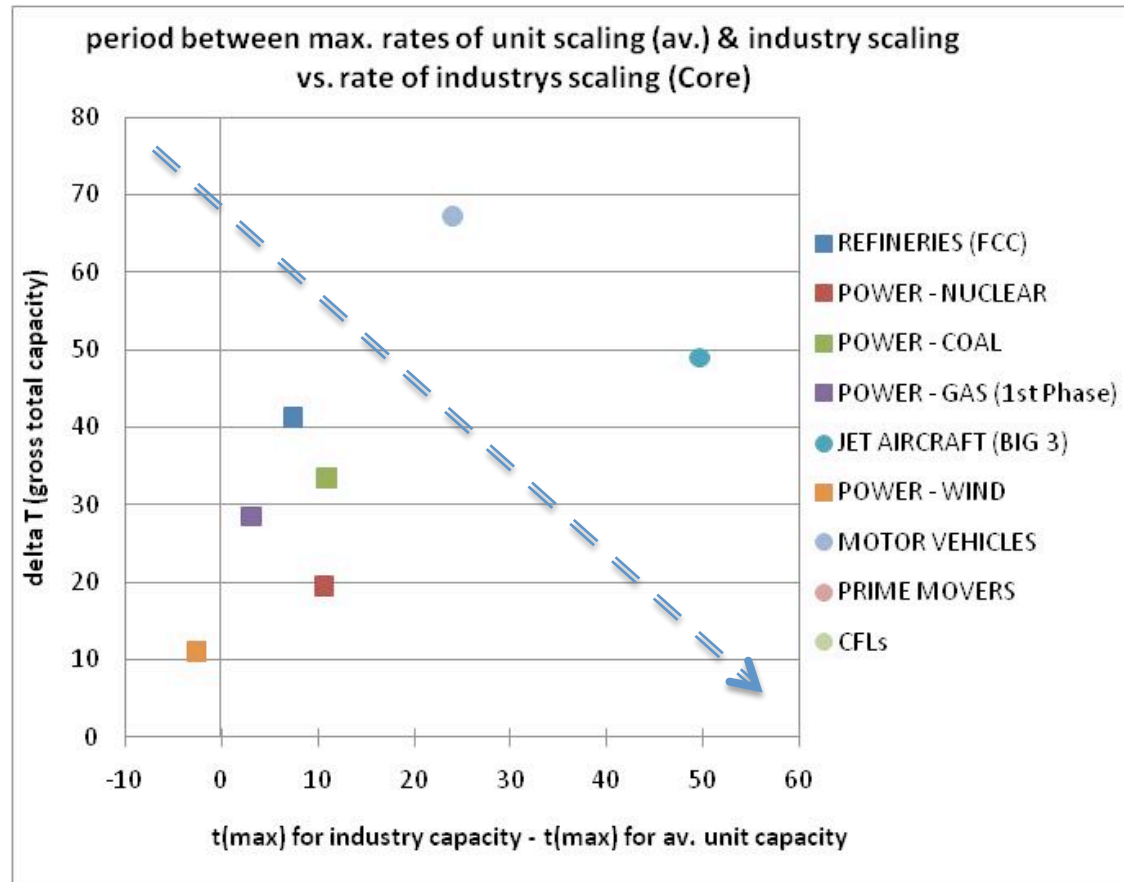


(1) Unit numbers drive industry growth (long experimentation phase)

(2) Unit scaling delayed despite technical scale economies

Do unit scaling dynamics determine rates of industry scaling?

y-axis:
rate of industry
scaling

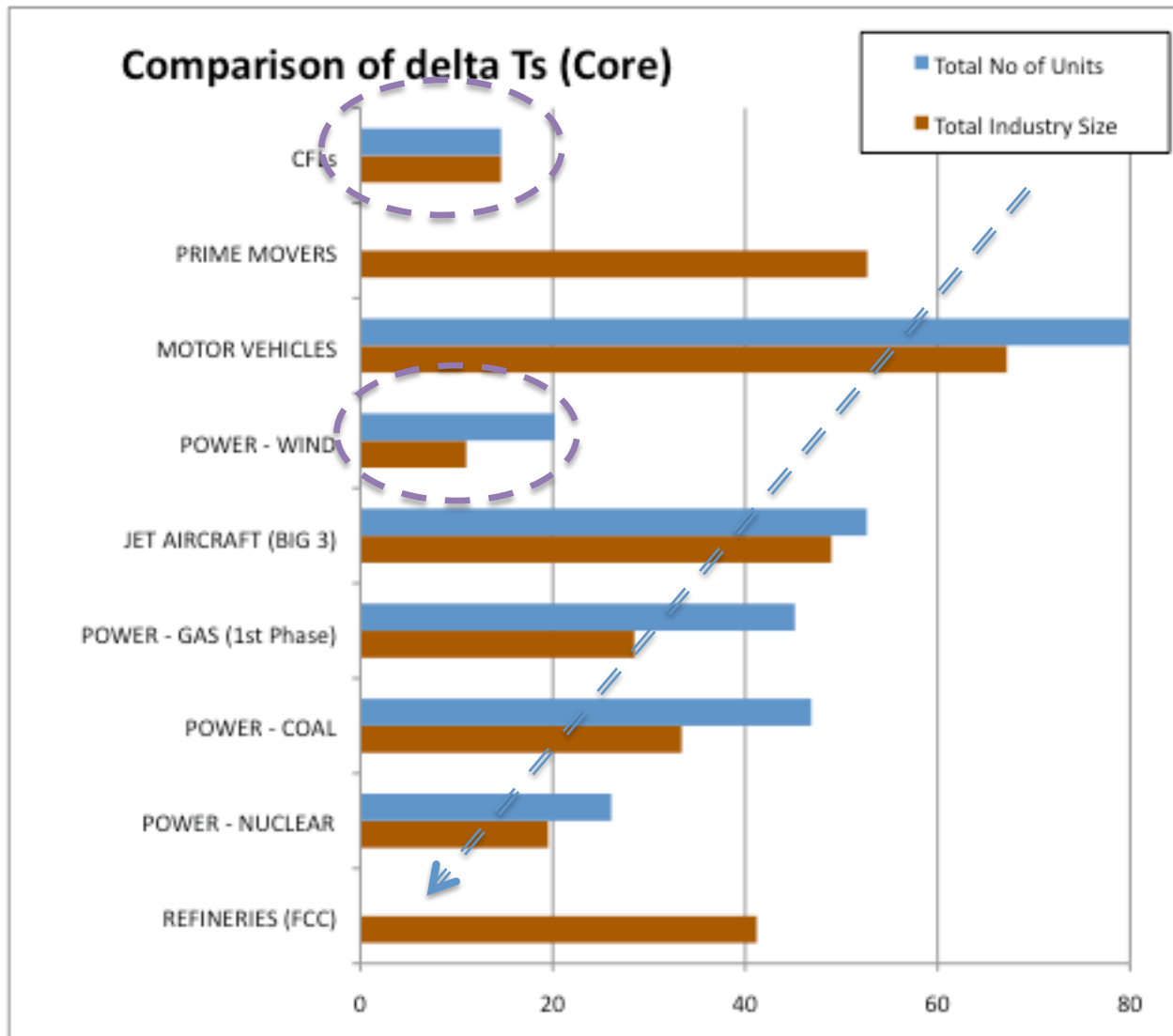


similar for
*faster unit
scaling*

x-axis: timelag from unit to industry scaling (measured at t_{max})
i.e., larger for *earlier* unit scaling (e.g., coal)

If unit scaling drives rate of industry scaling,
trend should be from top left to bottom right ...

Industry scaling is *generally* faster for technologies with larger unit sizes and less unit numbers



av. unit size
(MW)

K
(no of units)

10^{-6}

10^{11} to 10^{12}

?

?

10^{-1}

10^{10} to 10^{11}

10^0

?

10^1 to 10^2

10^5 to 10^6

10^1 to 10^2

10^5

10^2 to 10^3

10^4

10^3

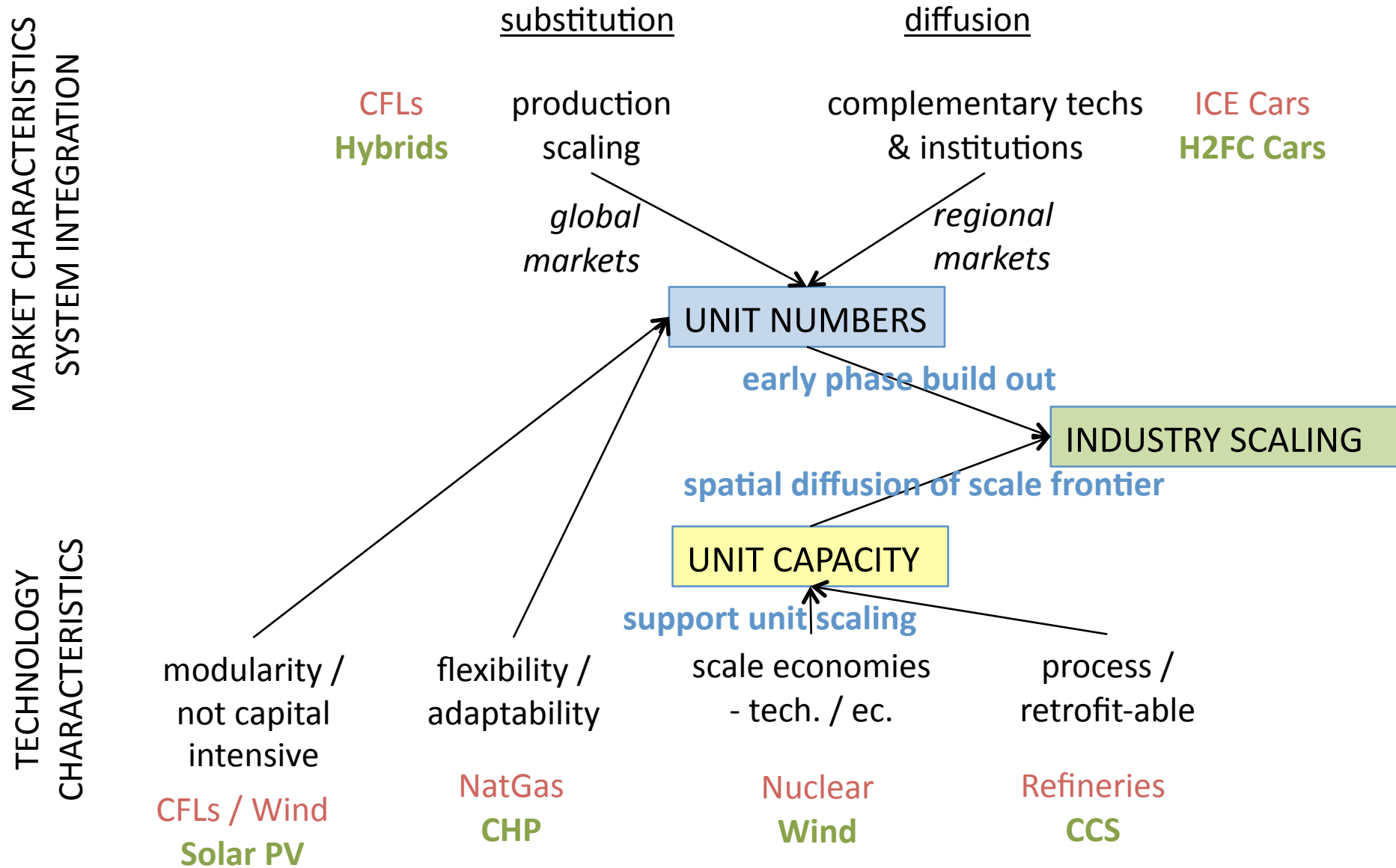
10^3

10^4

?

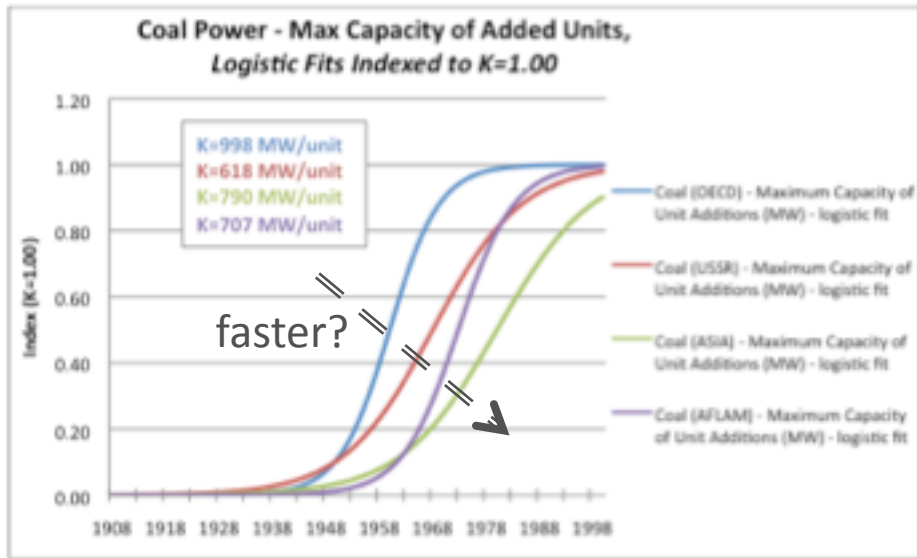
CFLs & wind: (i) substitution not diffusion; (ii) less capital intensive; (iii) global markets (more recent)

Summary: Different Routes to Industry Scaling

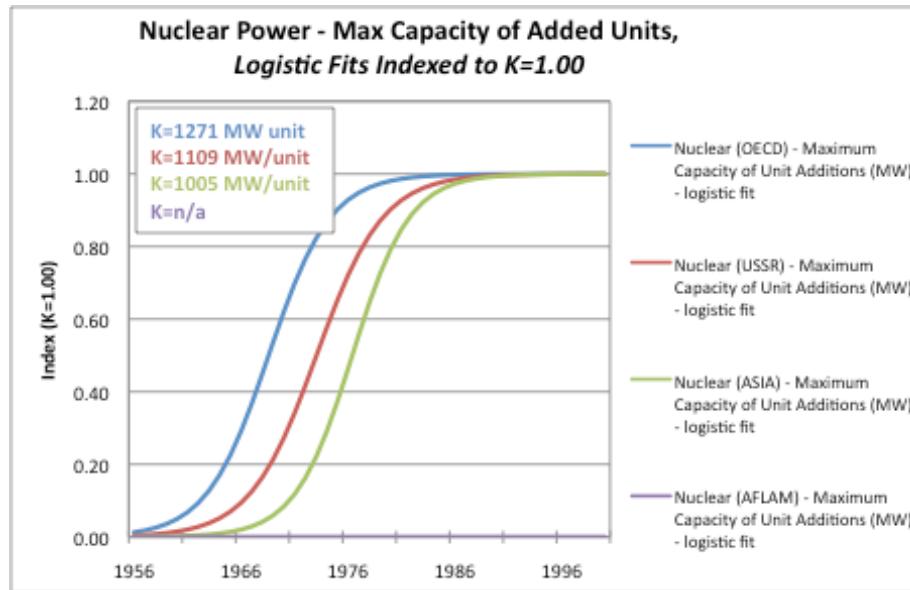


Spatial Diffusion of *Unit* Scaling

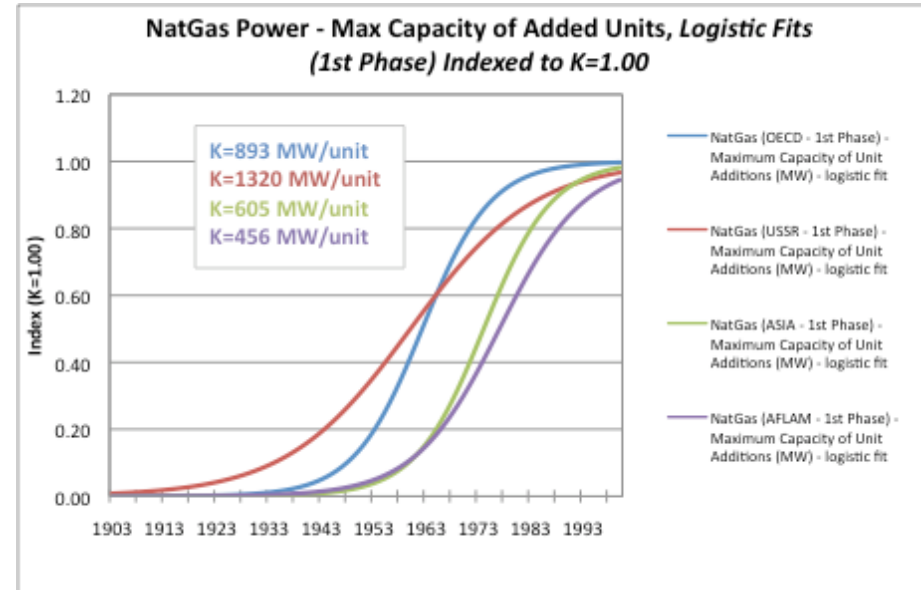
No consistent evidence for
‘leapfrogging’
of maximum unit capacity
from core to rim



delta T: Core < Periphery (Asia) > Rim



delta T: Core \approx Periphery



delta T: Core \approx Periphery (ex. USSR) \approx Rim

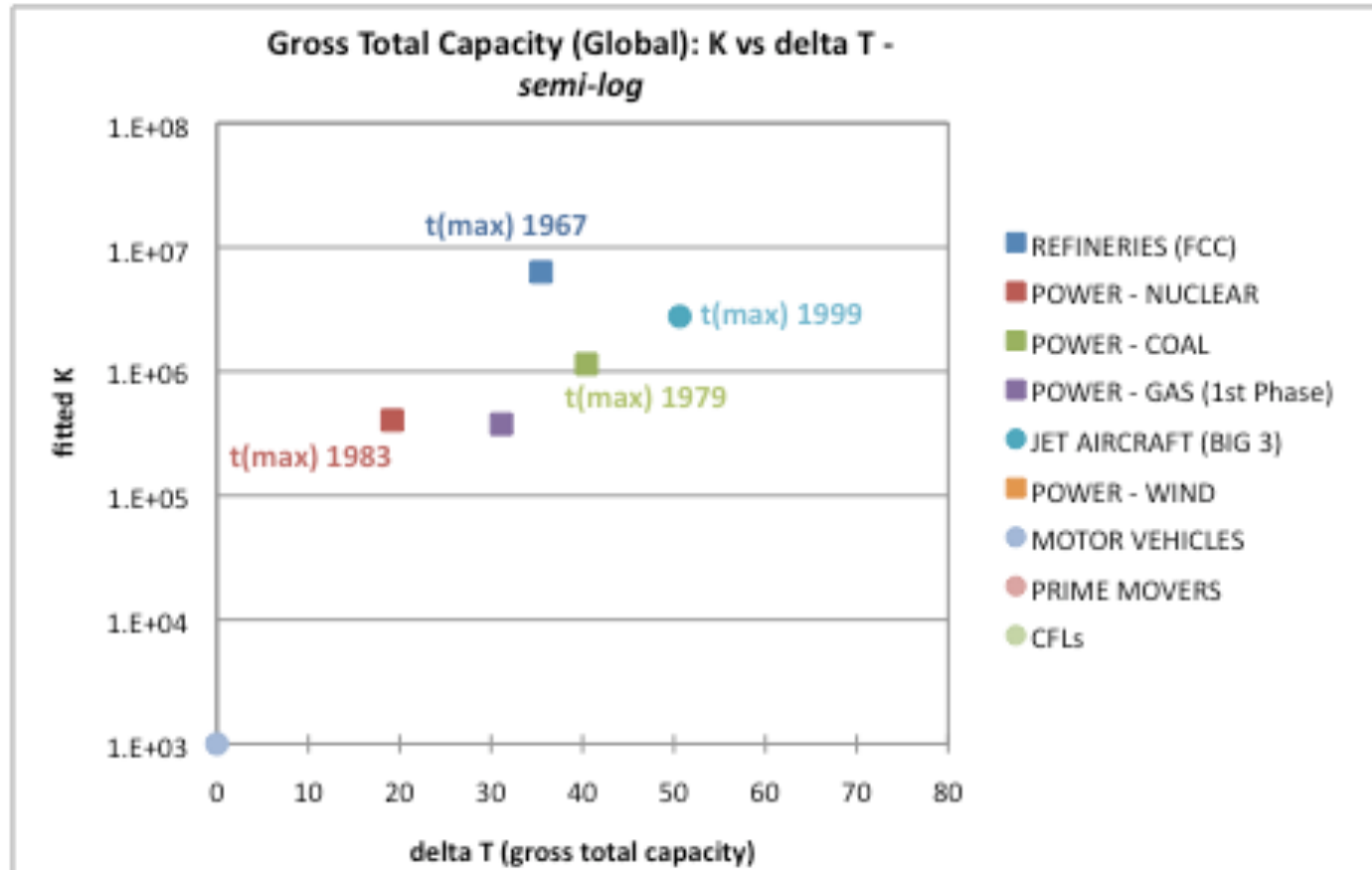
Key Findings:

Historical patterns of scaling in energy technologies

- Industry scaling is initiated *and* sustained by more unit numbers not larger unit sizes.
- Unit scale economies, if available, tend to be captured early.
- Unit scale economies do not diffuse spatially from core to rim markets.

- **The relationship between the rate and extent of industry scaling is consistent across technologies, and over time.**

Cross-technology comparisons of industry scaling need to control for growth in the overall size of 'the system'

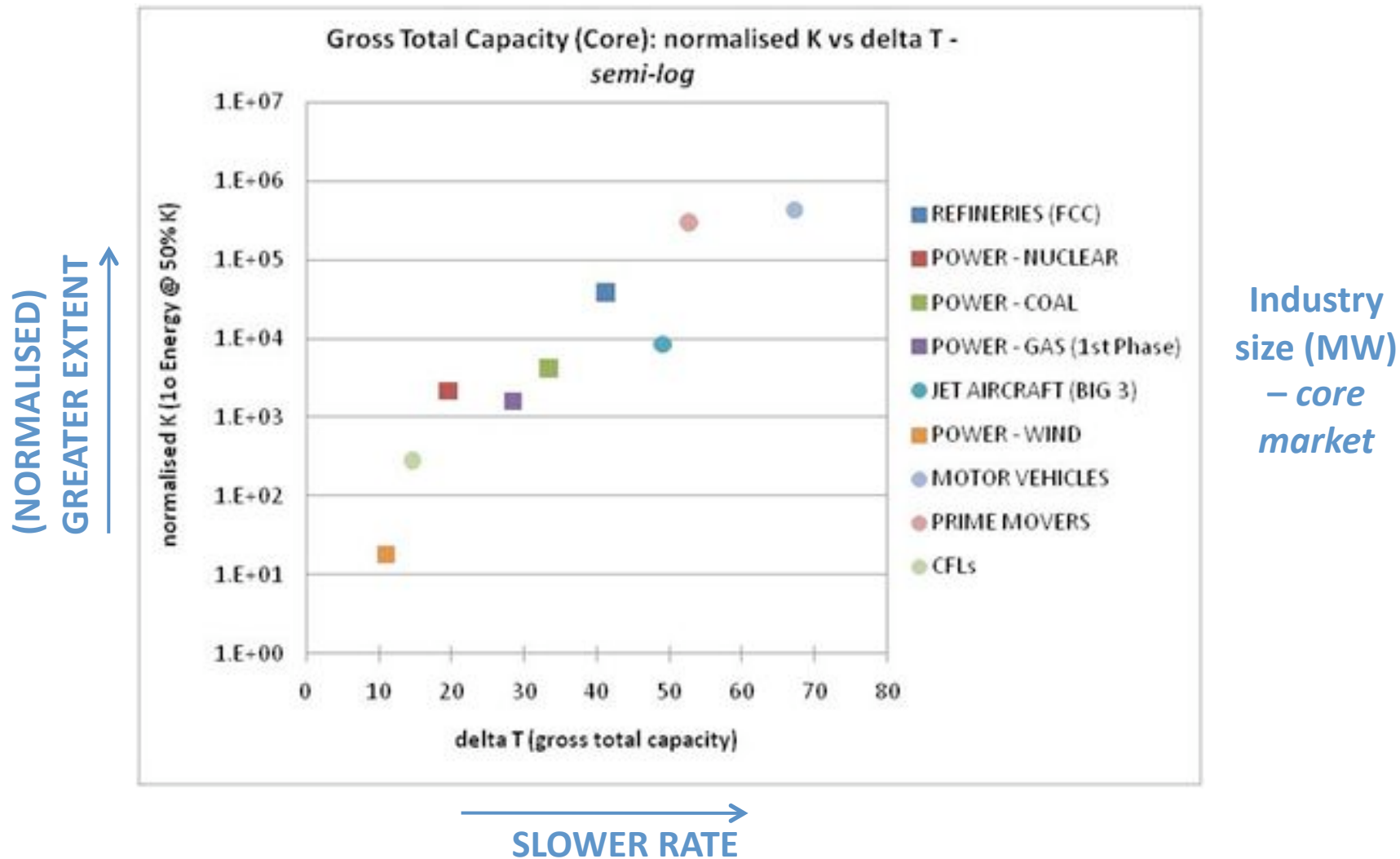


Industry size (MW) – global

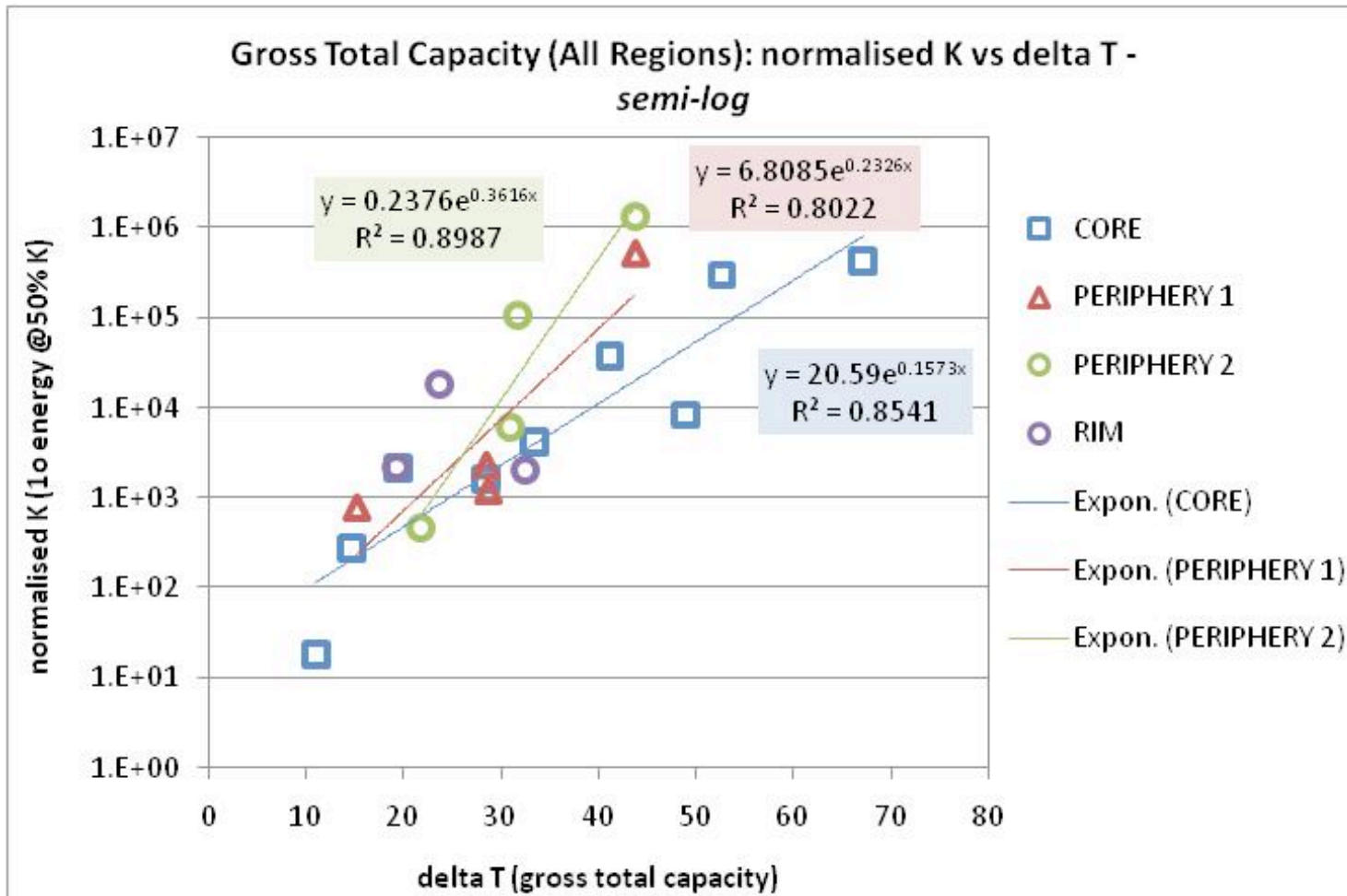
Capacity (K) is normalised into a common cross-technology metric of scale:

$$\text{Normalised } K = \frac{\text{MW carrying capacity}}{\text{Primary energy at } t(\text{max})}$$

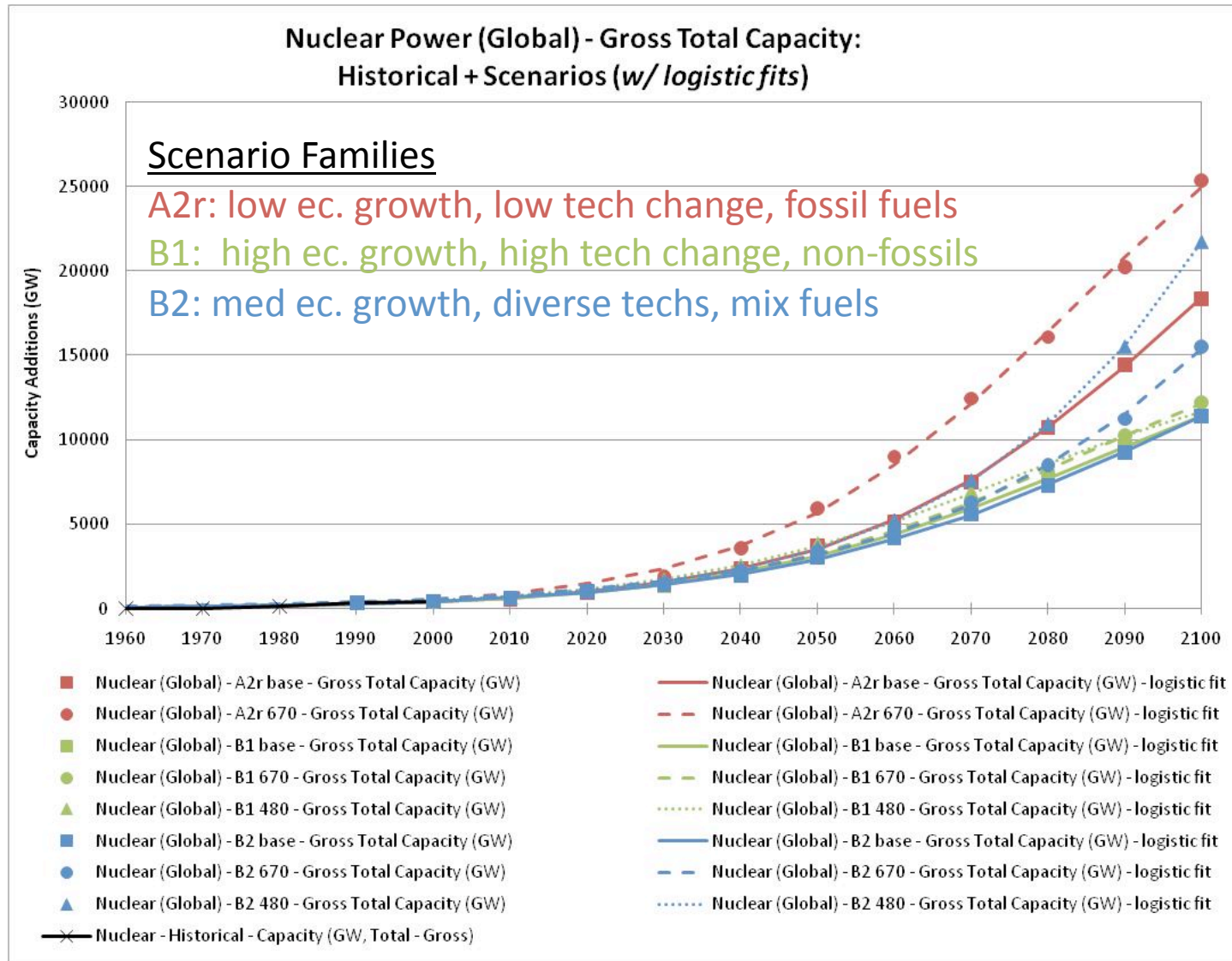
Historical relationship between EXTENT and RATE of industry scaling is consistent across technologies



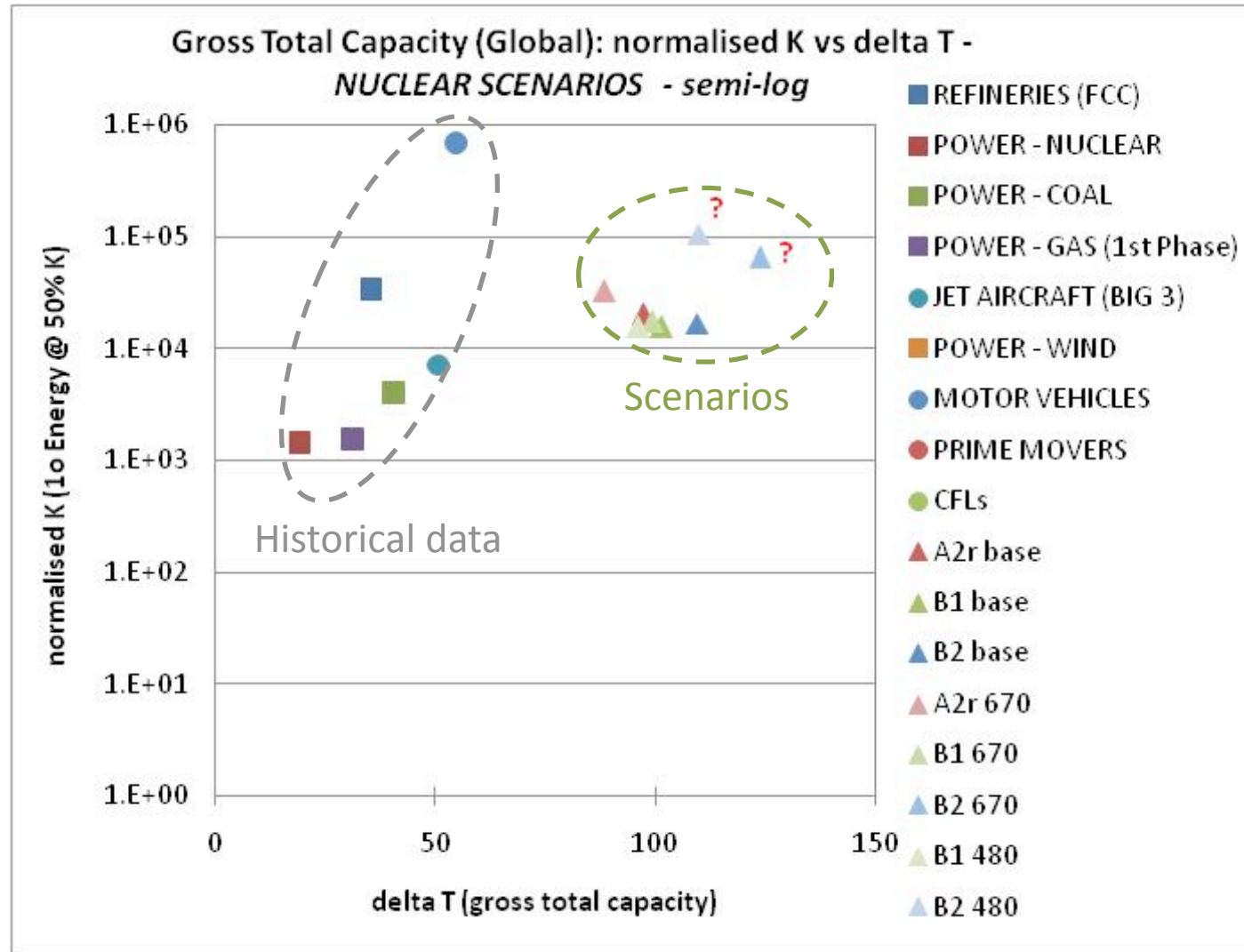
EXTENT – RATE relationship for industry size (MW) 'accelerates' from core to rim



Using RATE-EXTENT relationship to test scenarios: e.g., nuclear power – *discontinuous scaling at industry level?*

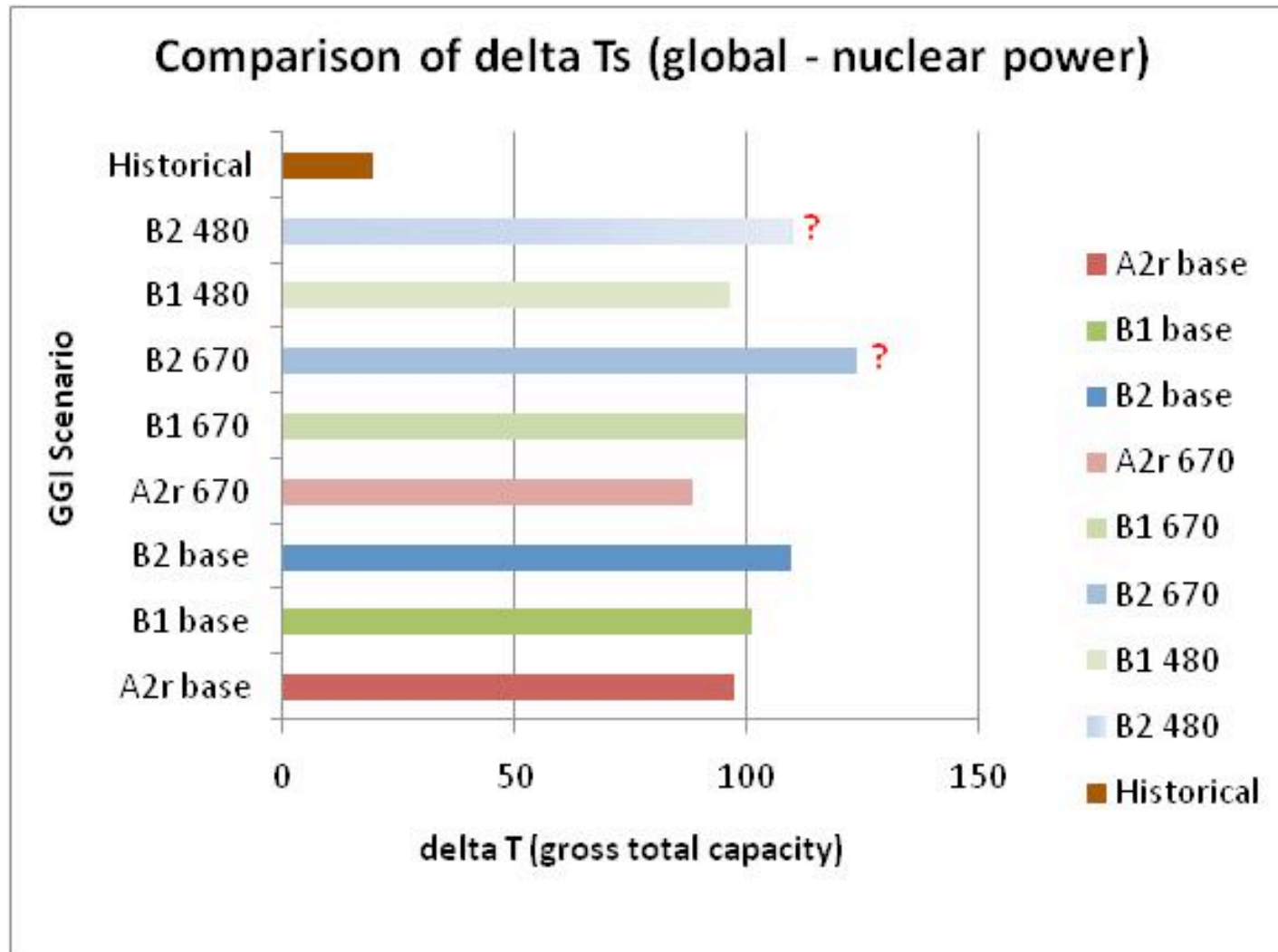


Normalised K vs. delta T relationships for nuclear scenarios actually appear conservative!



N.B. Each scenario normalized by its own projected total primary energy at t(max)

Why? 2 orders of magnitude higher K ... but much longer delta Ts



Take Home Messages

- Implications for low carbon technologies:
 - Drive early industry scaling by supporting build out of unit numbers (not larger unit sizes)
 - Support spatial diffusion of unit scale frontier (where appropriate).
 - Validate scaling assumptions in scenarios using historical rate-extent relationship.
- Next steps:
 - Integrate scaling dynamics with qualitative conceptual framework.
- More info:
 - wilsonch@iiasa.ac.at
 - IIASA Interim Report available soon with all data & analysis