Lessons from Historical Energy Transitions for Addressing Climate Change and Sustainable Development

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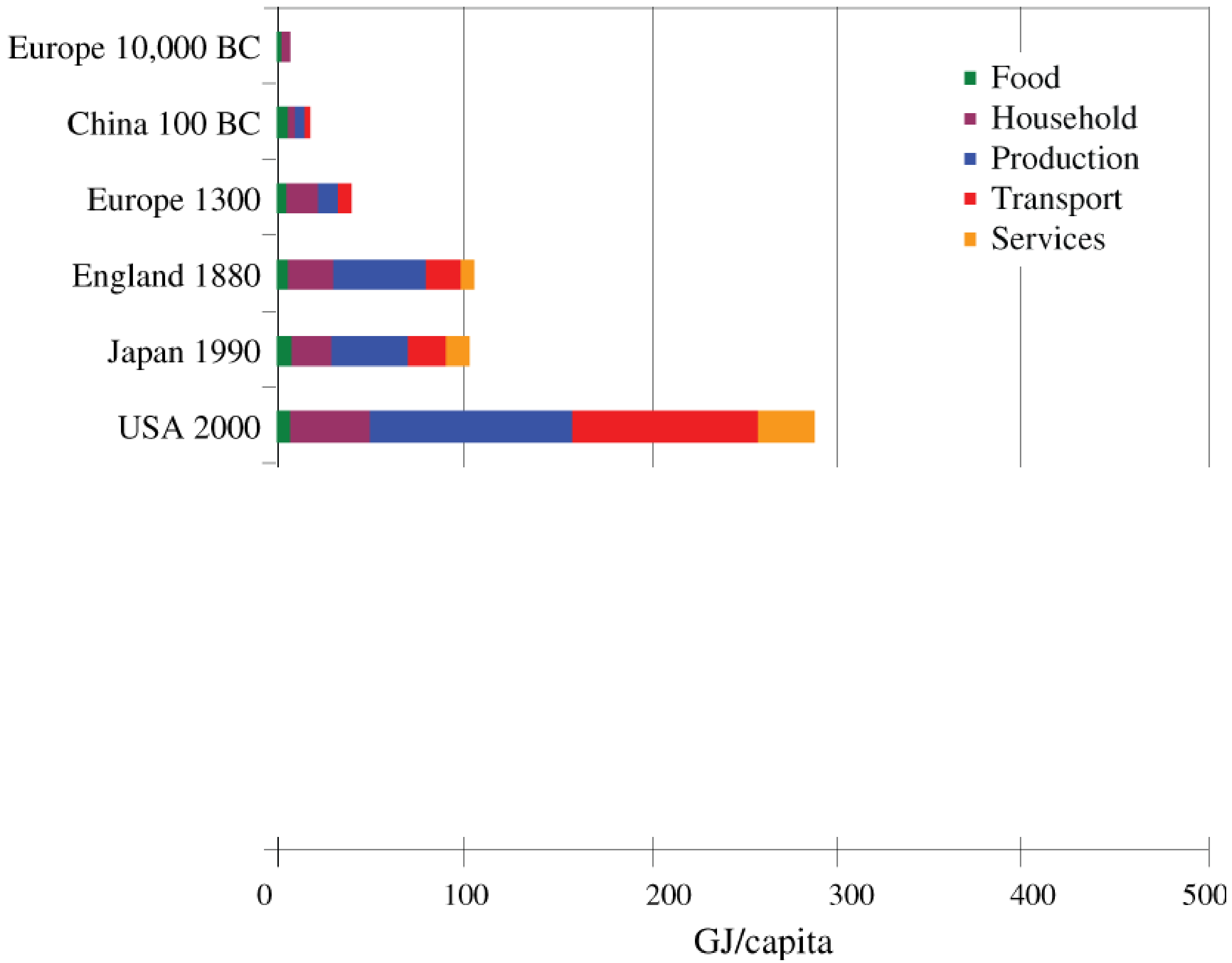
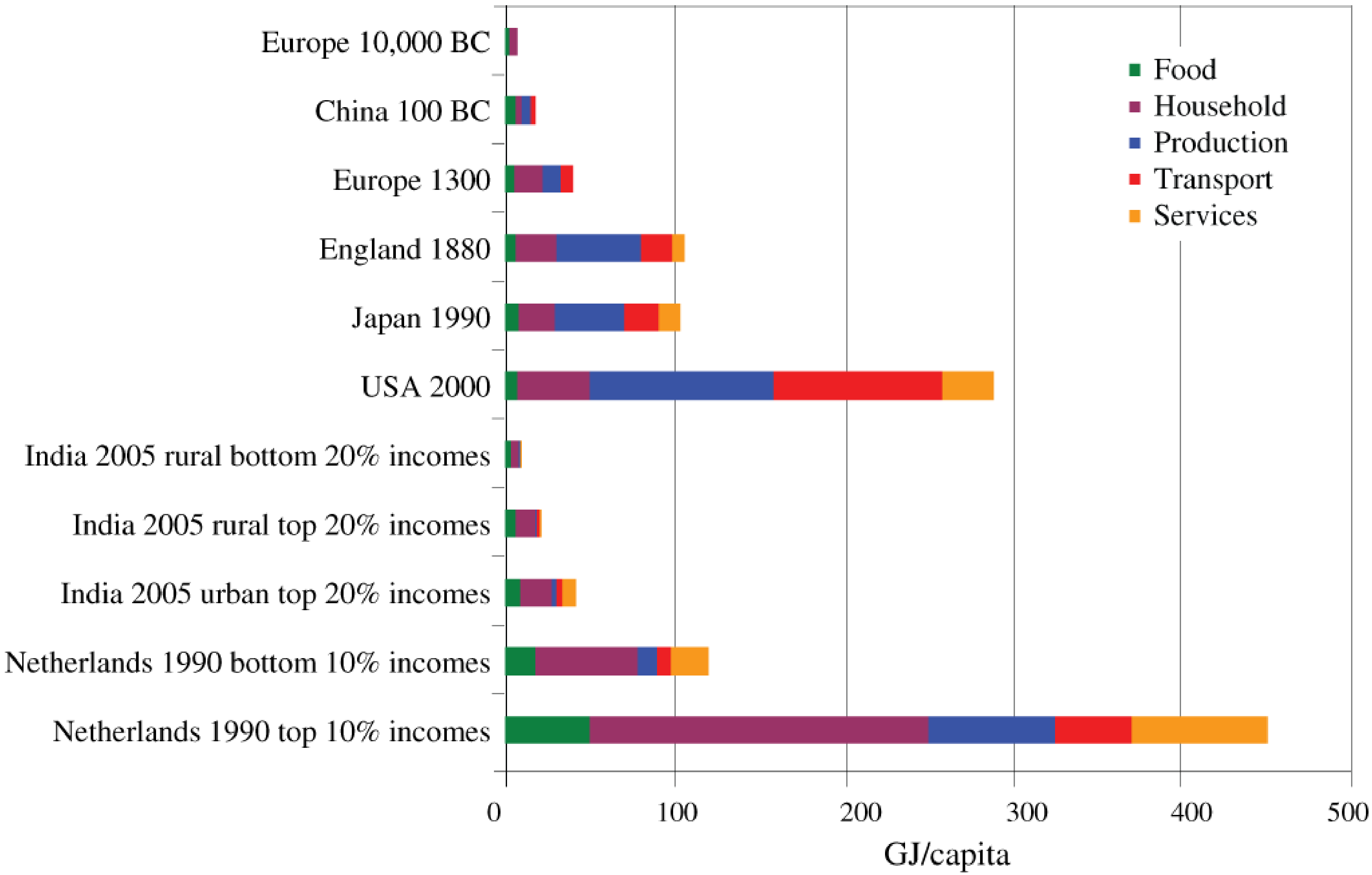
RITE International Symposium 2012, Tokyo, February 7, 2012

Energy Transitions: Past



Source: adapted from V. Smil, 1994

Energy Transitions: Present (unfinished business)

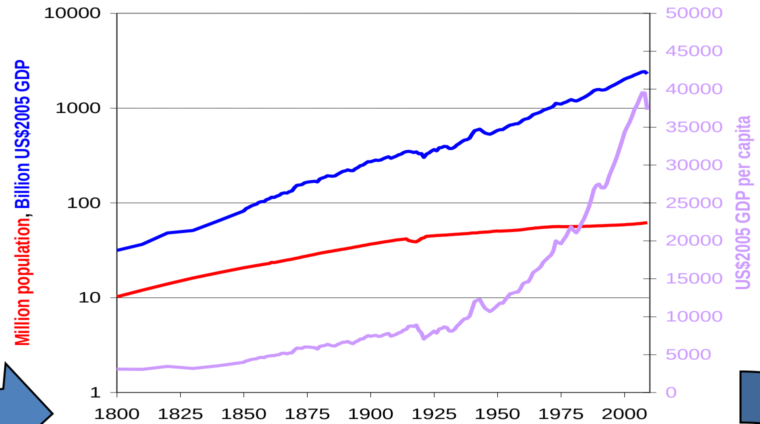


Source: Global Energy Assessment (GEA) KM1, 2012 (in press)

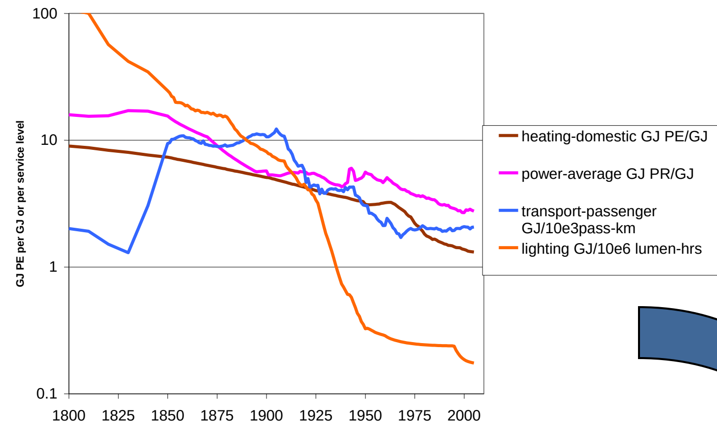
UK Energy History

A positive feedback loop driven by energy service demand & innovation

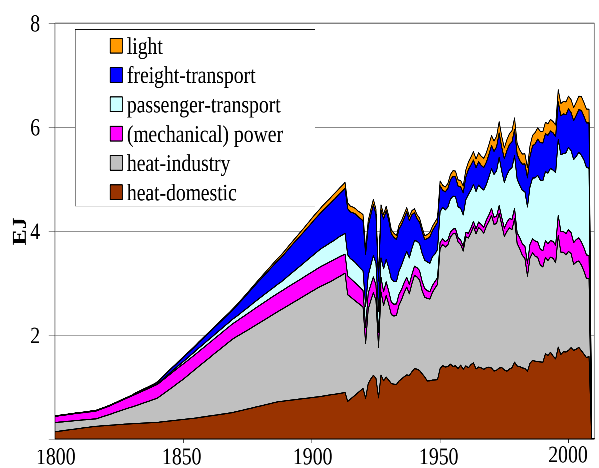
Population and Income



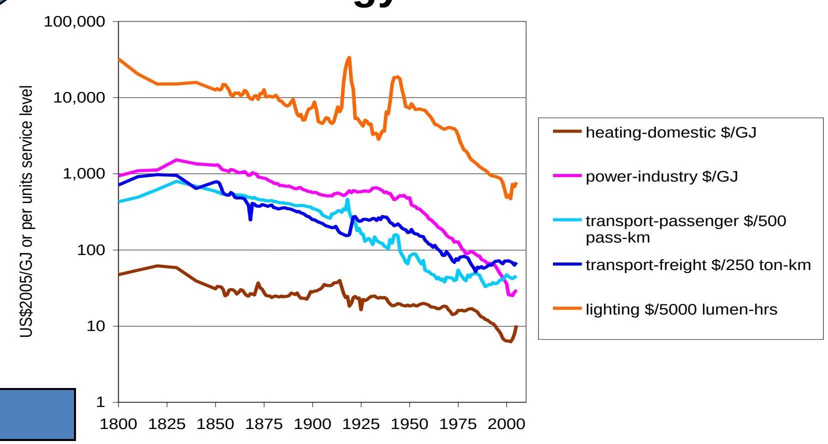
Innovation and LbD: efficiency of end use



Energy service demands

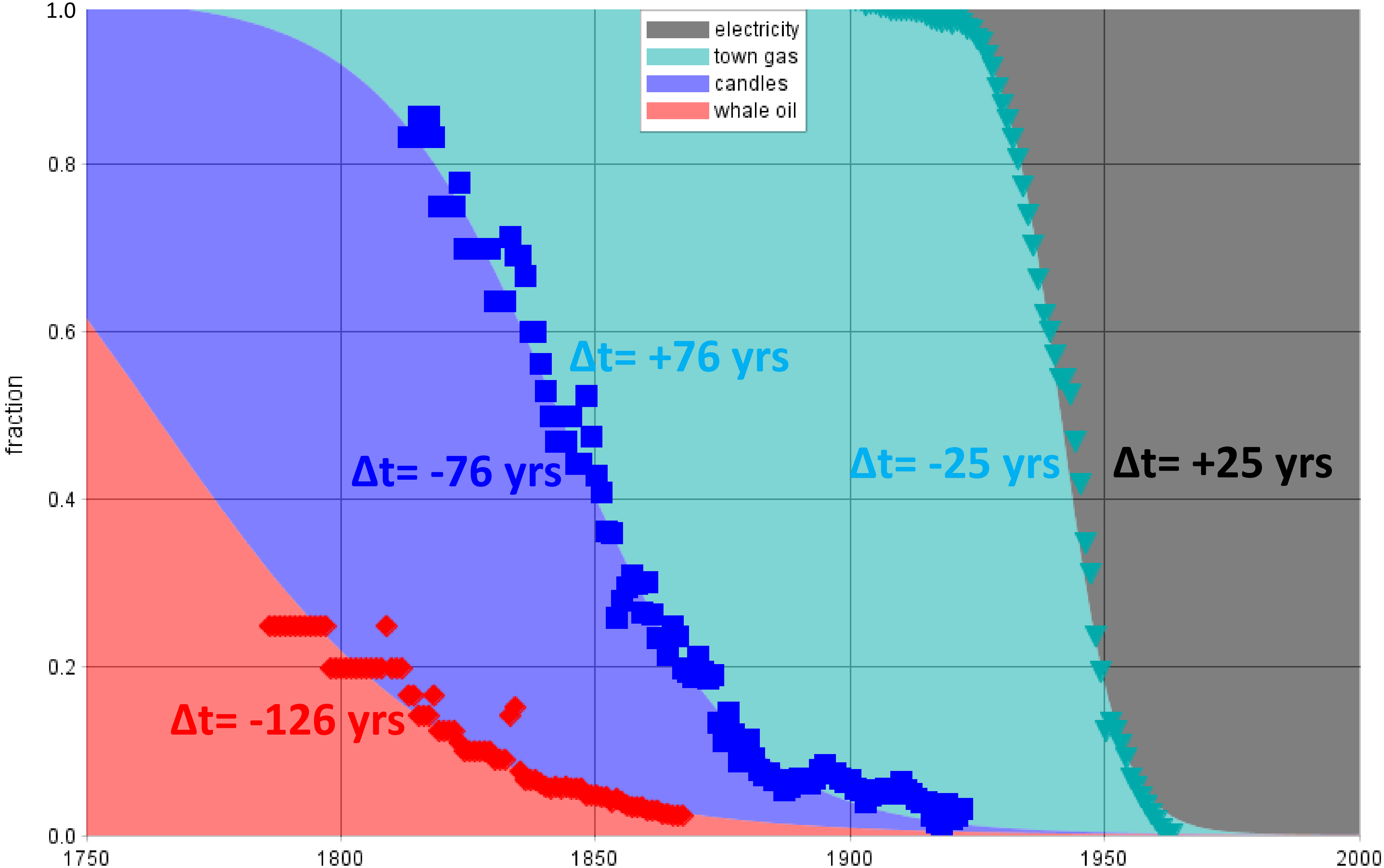


+Market growth and LbD: cost of energy services



Source: Global Energy Assessment (GEA) KM1, 2012 (in press)

UK – Transitions in Energy Services for Light



Source: Grubler (in press) based on Fouquet, 2008.

Energy Transitions - Climate Protection & Sustainability

- End-use (efficiency) and consumer benefits are key
- Innovation is key but needs to be leveraged systemically and stably
- Deep uncertainty requires risk hedging (adaptation) and innovation portfolio approach
- Powerful patterns: scaling, experimentation, learning

Importance of Energy End-use

- Least efficient part of energy system
- Vast improvement potentials
- Dominant in terms of installed capacity
- Dominant form of energy investment (and GDP & employment multipliers!)

Capacity of US Energy Conversion Technologies

GW (rounded)		1850	1900	1950	2000
stationary	thermal (furnaces/boilers)	*300*	*900*	*1900*	*2700*
end-use	mechanical (prime movers)	1	10	70	300
	electrical (drives, appliances)	*0*	*20*	*200*	*2200*
mobile	animals/ships/trains/aircraft	5	30	120	260
end-use	automobiles	0	0	3300	25000
stationary	thermal (power plant boilers)	*0*	*10*	*260*	*2600*
suppply	mechanical (prime movers)	0	3	70	800
	chemical (refineries)	0	8	520	1280
TOTAL		306	981	6440	35140

Energy end-use = 30 TW or 87% of all energy conversion technologies
= 5 TW or 50% when excluding automobiles

Source: GEA KM24, 2012

World Energy Technology Innovation Investments (Billion $)

	innovation (RD&D)	market formation	diffusion
End-use & efficiency	>>8	5	300-3500
Fossil fuel supply	>12	>>2	200-550
Nuclear	>10	0	3-8
Renewables	>12	~20	>20
Electricity (Gen+T&D)	>>1	~100	450-520
Other*	>>4	<15	n.a.
Total	>50	<150	1000 - <5000
non-OECD	**~20**	**~30**	**~400 - ~1500**
non-OECD share	**>40%**	**<20%**	**40% - 30%**

* hydrogen, fuel cells, other power & storage technologies, basic energy research

Source: GEA KM24, 2011

Innovation Systems

- Change requires systemic approach invoking <u>all</u> innovation phases and processes:
  - R&D, niche markets, diffusion, obsolescence
  - learning, actors/institutions, resources, technology (hardware+software)

- Important biases at all stages:
  R&D: supply side bias (nuclear, fossil)
  niche markets: supply side bias (solar/wind)
  diffusion: huge distortions via fossil fuel subsidies
  obsolescence: “grandfathering” of old/”dirty”

- Few systemic approaches & successes

The Space of ETIS

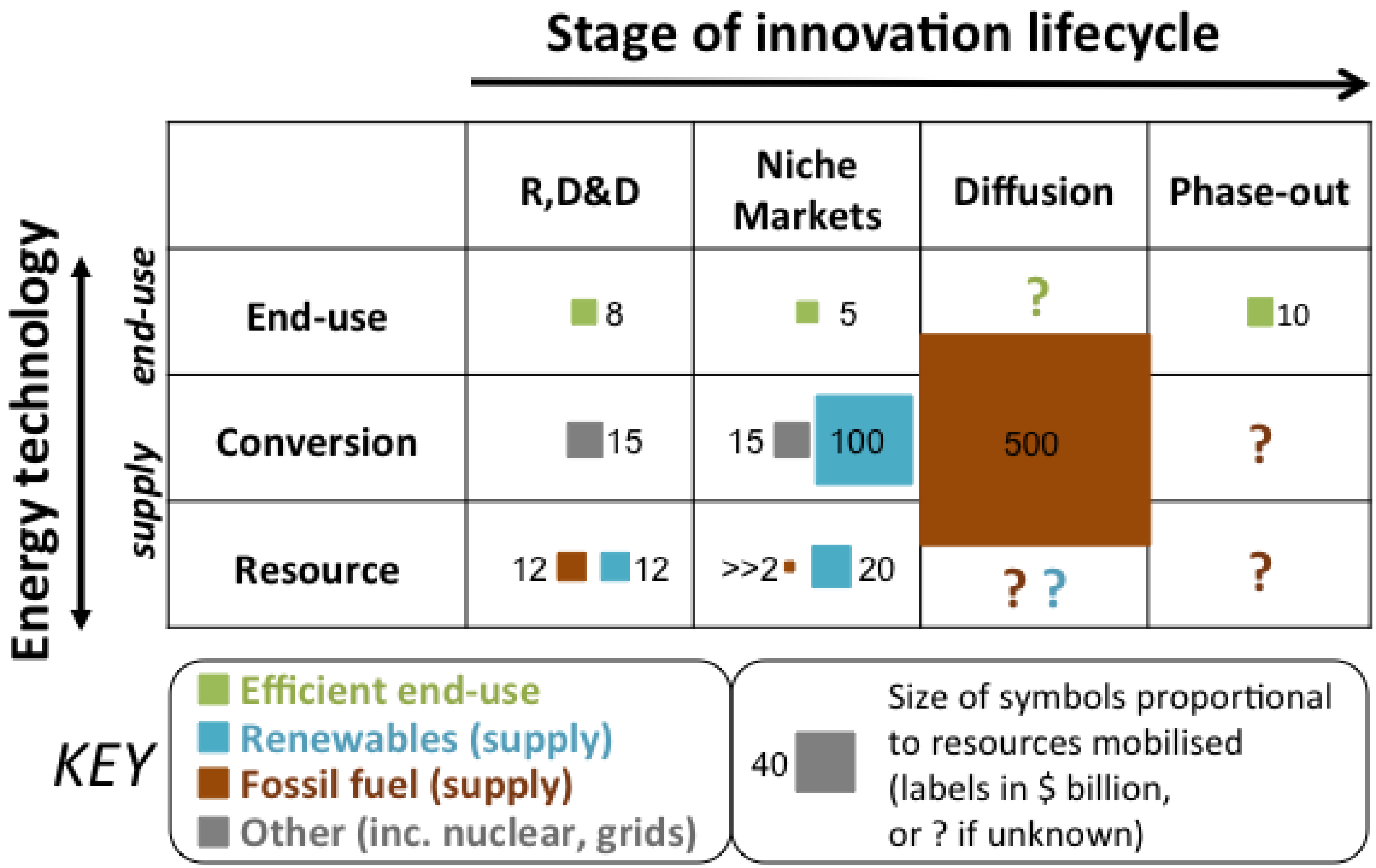
Innovation life cycle stage

Energy system component (technologies)

	R&D	Niche Markets	Diffusion	Phase-out
End use (energy services)				
Conversion (to fuels/electricity)				
Supply (Resource extraction)				

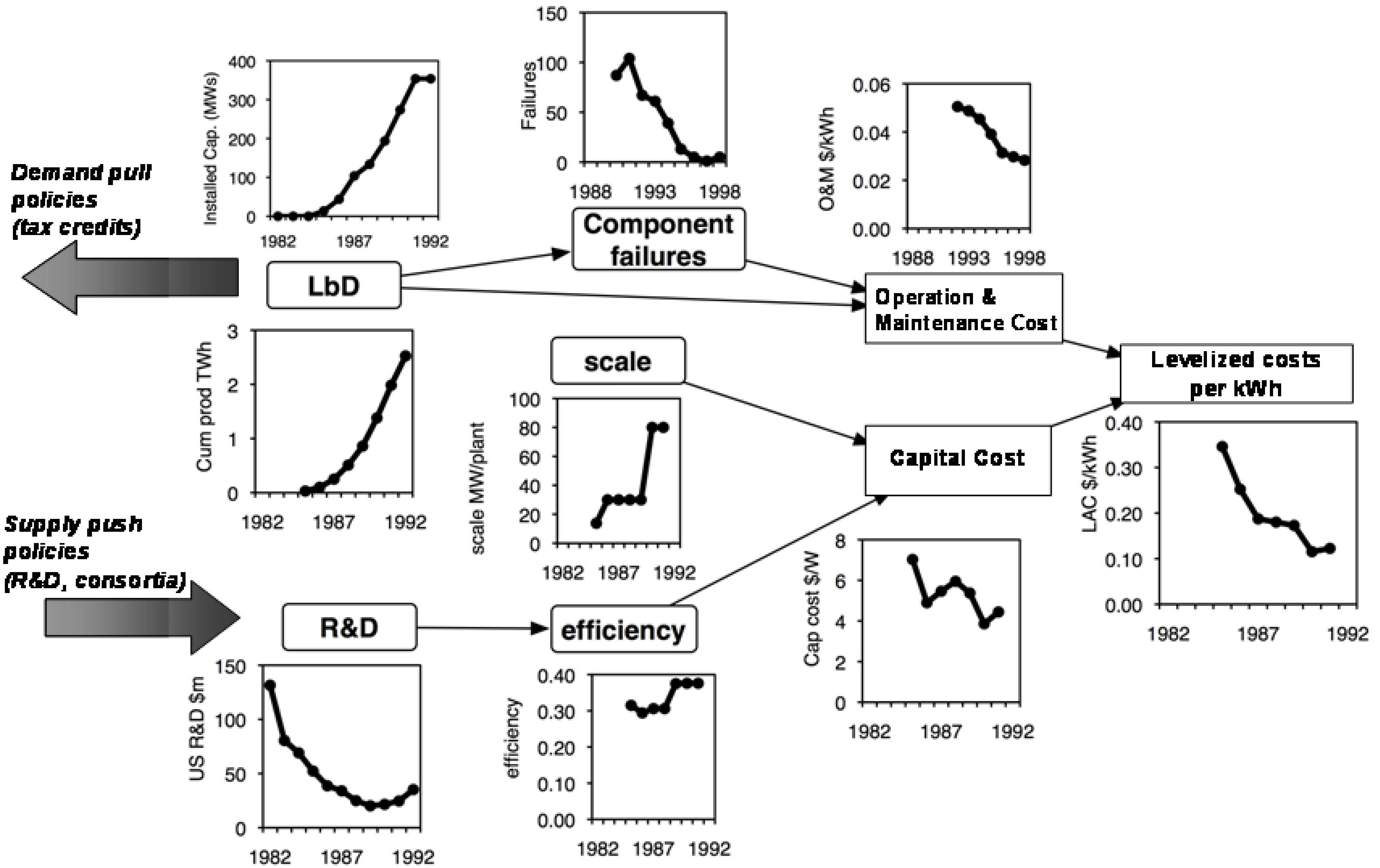
Levels of investment & capital depreciation

Current Public ETIS Policy Focus
(policy-induced resource mobilization, billion US$2005)



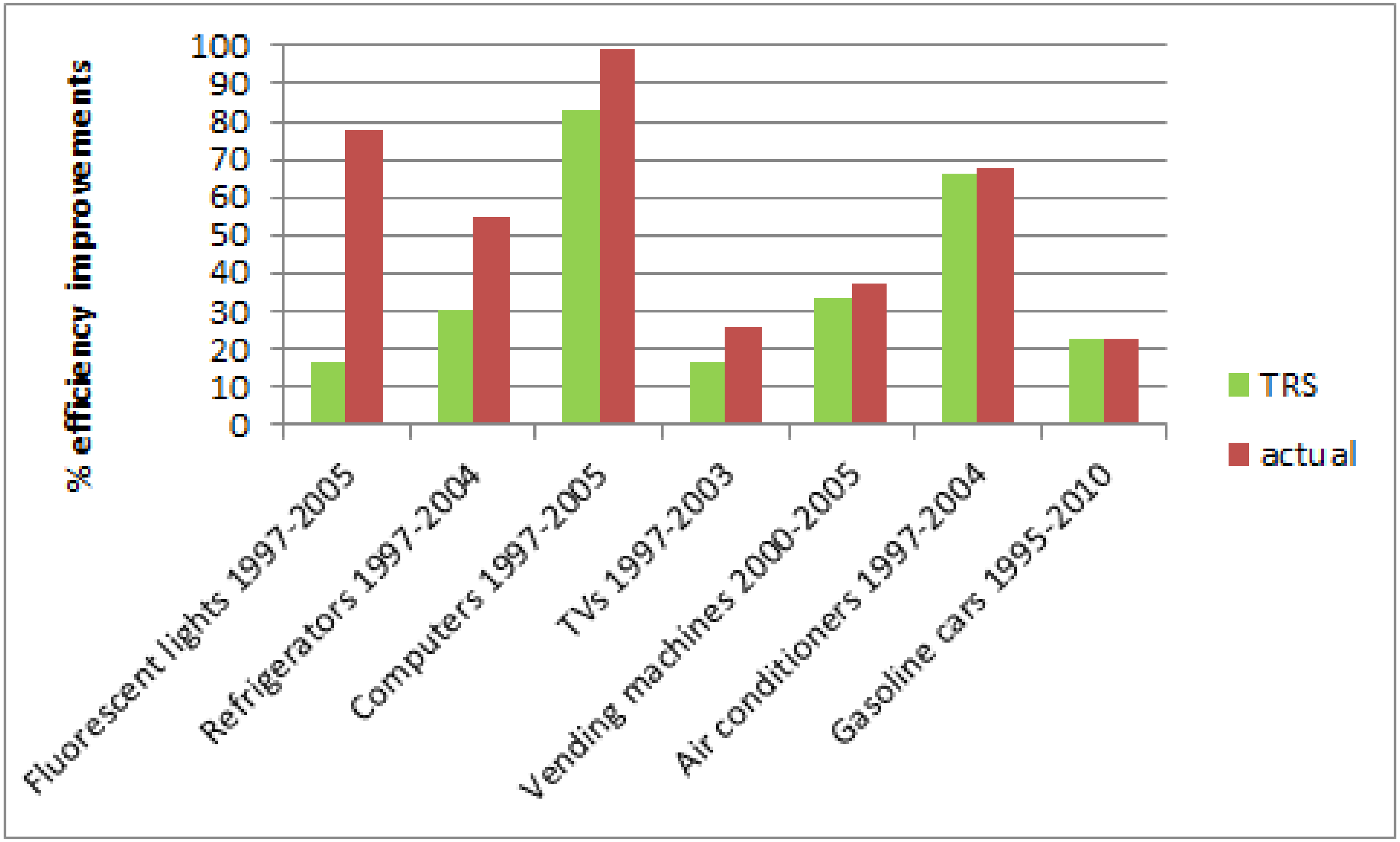
Source: Wilson et al., (in press)

US Solar Thermal Virtuous Development Cycle 1982-1992



Source: GEA KM24, 2012 based on G. Nemet, 2011

Japan: Efficiency Improvements
Top-Runner Standard vs Actual Achieved



"Top-Runner": Joint industry-government dynamic standard setting that incentivizes innovation

Source: GEA KM24, 2012

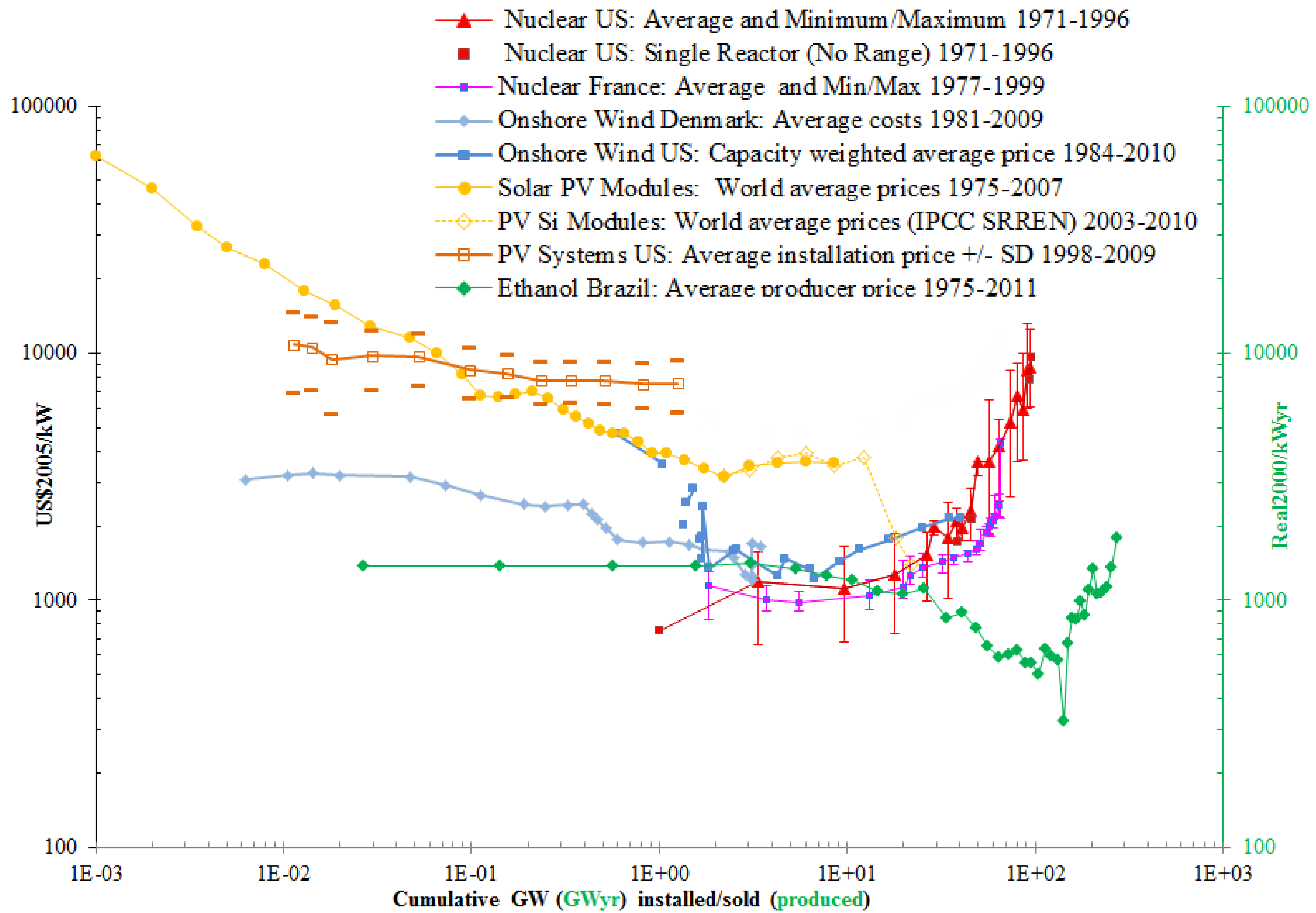
Patterns of Technological Change

- Learning (unlearning): improvements contingent on market deployment (with uncertain outcomes)
  Importance of granularity and continuity (knowledge depreciation)

- Scaling (5 phases in all successful technologies)
  Importance of prolonged early experimentation at small unit scales

- Catch up (late-starters with faster diffusion)
  Importance of learning and international technology collaboration

Post Fossil Energy Supply Technologies Cost Trends



Source: GEA KM24, 2012

Explaining the Doubling Price (750 to 1500 $/kW) of US Wind Turbines (US$/kW)

	2002-2008	2009-2010
Endogenous	**+376**	**-37**
Labor costs*	+91	+12
Warranty/Profits**	+101	-98
Scaling-up	+184	+57
Exogenous	**+219**	**-53**
Material/energy costs	+83	-38
Currency fluctuations	+136	-15
Residual	+155	-105
Total price change	**+750**	**-195**

Source: Bolinger&Wiser, 2012. * denotes potential underestimates (accounting for residual)

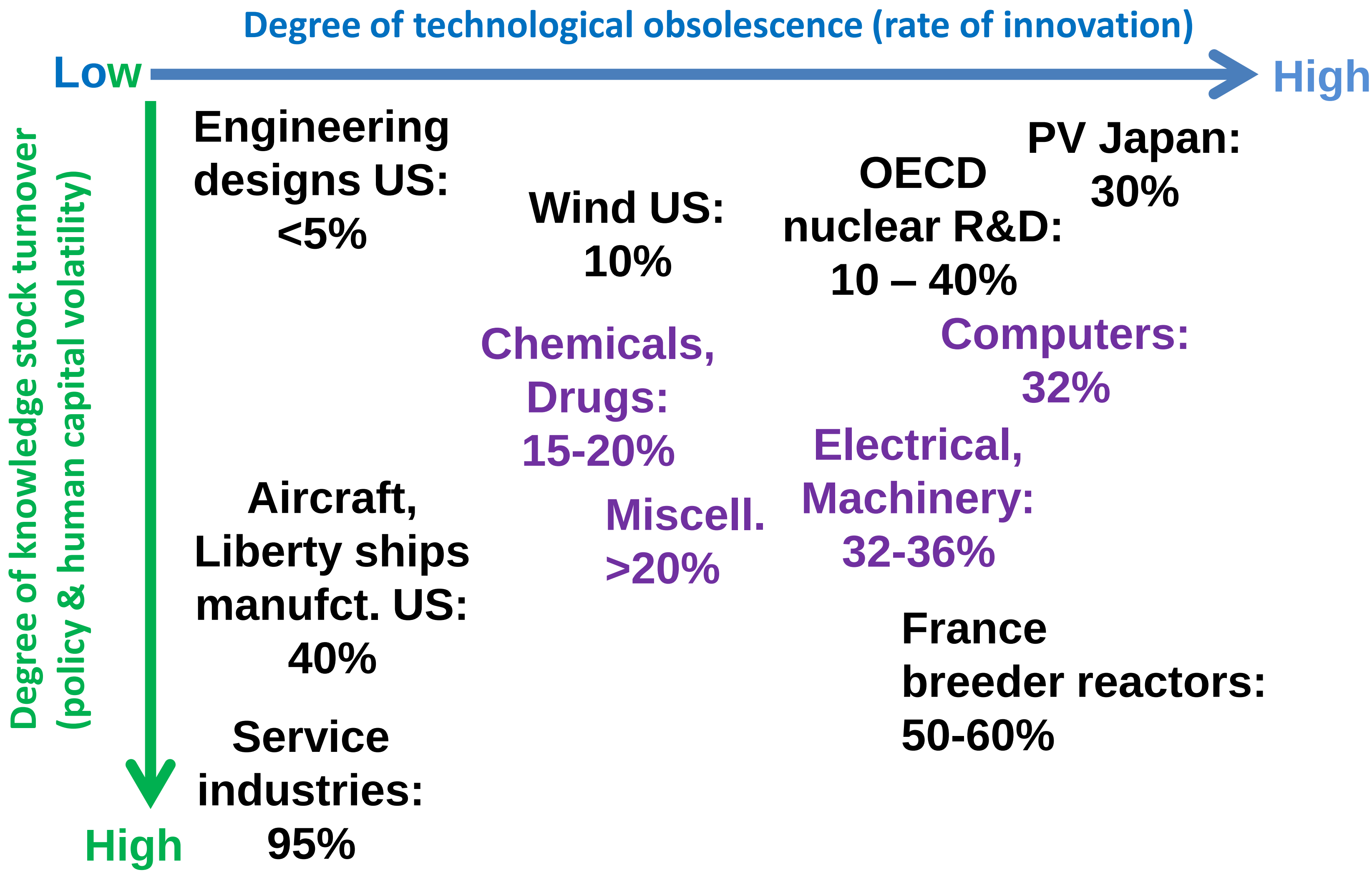
Learning rates and cumulative experience (# of units produced/sold) for energy technologies

category	technology	data for:	cumulative production (units) #	exp	period	learnin rate
energy end-use	Transitors	World	>1	10^18	*1960-2010*	40
	DRAMs	World	>1	10^11	*1975-2005*	16 - 24
	Automobiles	World	>2	10^9	*1900-2005*	9 - 14
	Washing machines	World	>2	10^9	*1965-2008*	33 ±9
	Refrigerators	World	>2	10^9	*1964-2008*	9 ±4
	Dishwashers	World	>6	10^8	*1968-2007*	27 ±7
	Freezers (upright)	World	>6	10^8	*1970-2003*	10 ±5
	Freezers (chest)	World	>5	10^8	*1970-1998*	8 ±2
	Dryers	World	>3	10^8	*1969-2003*	28 ±7
	Hand-held calculators	US	>4	10^8	*early 1970s*	30
	CF light bulbs	US	>4	10^8	*1992-1998*	16
	A/C & heat pumps	US	>1	10^8	*1972-2009*	18 ±1
	Air furnaces	US	>1	10^8	*1953-2009*	31 ±3
	Solar hot water heaters	US	>1	10^6	*1974-2003*	-3
	average for end-use technologies			**10^9**		**20**
energy supply	PV modules	World	>1	10^10	*1975-2009*	18-24
	Wind turbines	World	>1	10^5	*1975-2009*	10-17
	Heat pumps	S, CH	<1	10^5	*1982-2008*	2 - 21
	Gas turbines	World	>4	10^4	*1958-1980*	10-13
	Pulverized coal boilers	World	>6	10^3	*1940-2000*	6
	Hypropower plants	OECD	~5	10^3	*1975-1993*	1
	Nuclear reactors	US, France	<1	10^3	*1971-2000*	-20 - -47
	Ethanol	Brazil	<1	10^3	*1975-2009*	21
	Coal power plants	OECD	<1	10^3	*1975-1993*	8
	Coal power plants	US	<1	10^3	*1950-1982*	1 - 6
	Gas pipelines	US	<1	10^3	*1984-1997*	4
	Gas combined cycles	OECD	<1	10^3	*1981-1997*	10
	Hydrogen production (SRM)	World	>1	10^2	*1980-2005*	27
	LNG production	World	>1	10^2	*1980-2005*	14
	average for suppy technologies					**8**
	average for supply, excluding nuclear			**10^4**		**12**

Knowledge Depreciation Rates

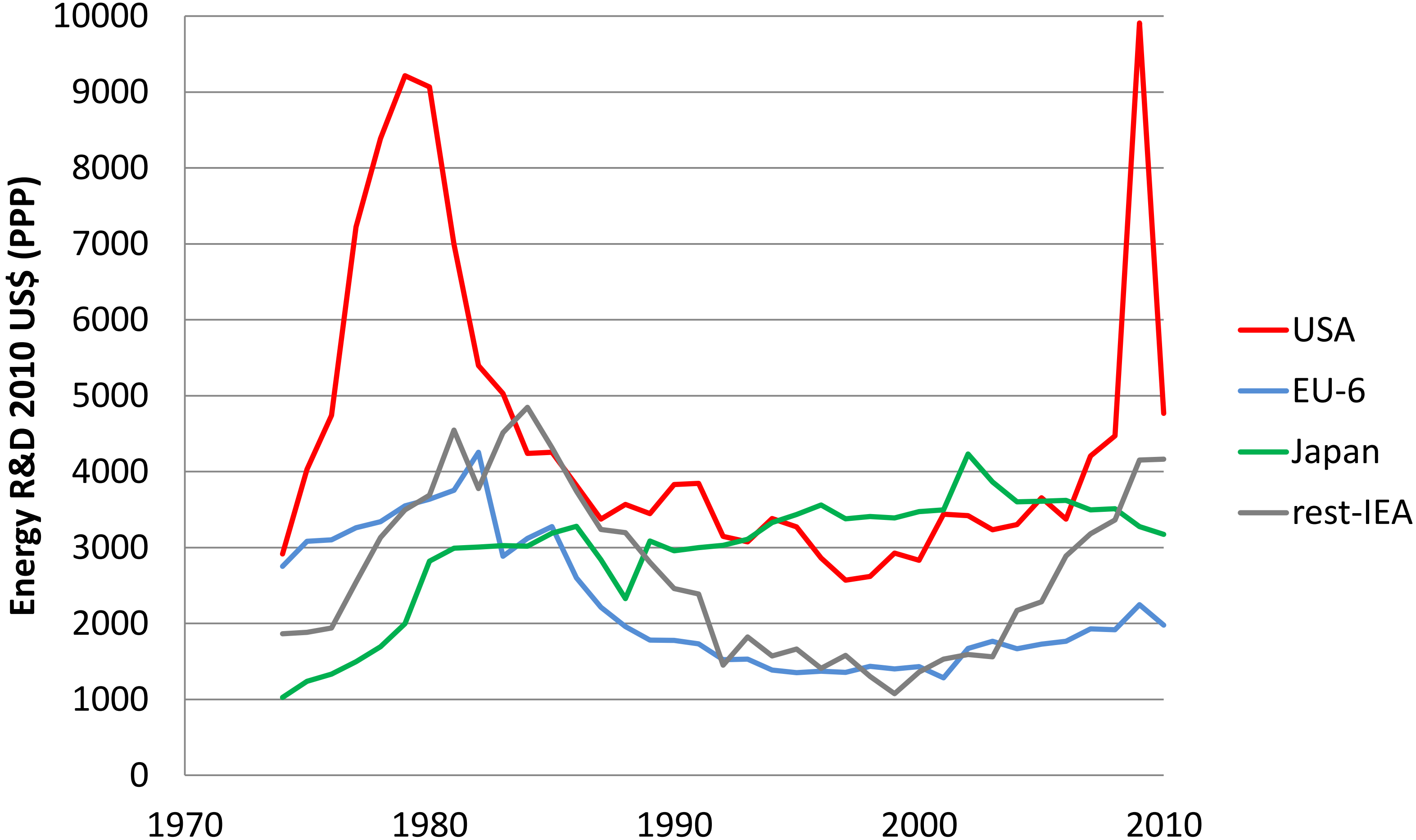
Knowledge Depreciation Rates (% per year)

empirical studies reviewed GEA KM24 (2012) and
modeled R&D deprecation in US manufacturing (Hall, 2007)



IEA Energy R&D Trends: Boom-and-Bust Cycles (Million $$_{PPP2010}$)

BRIMCS: ~18,000



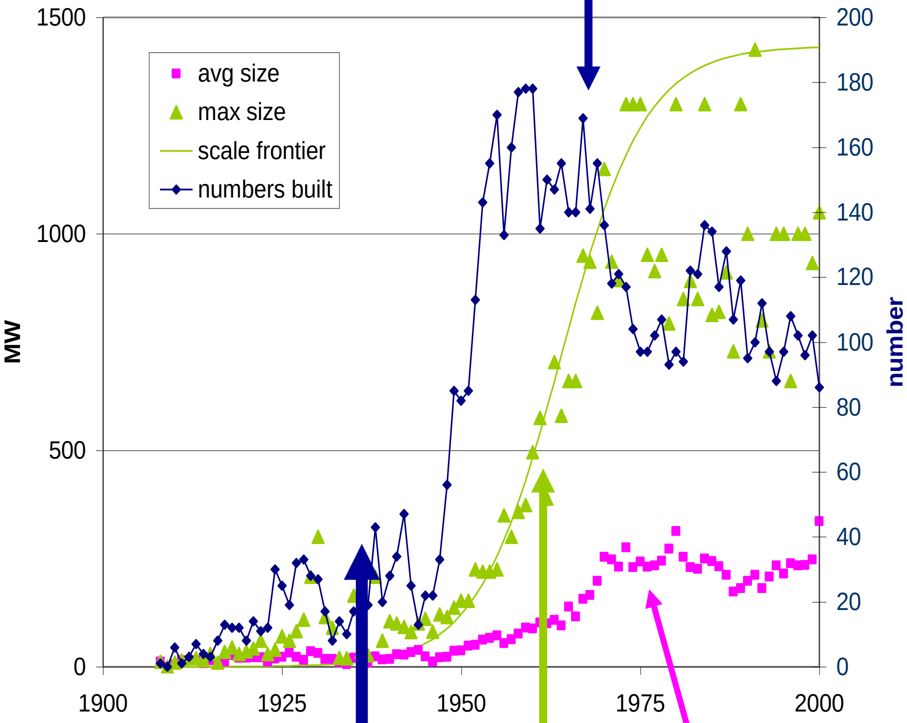
Robust Patterns in Technology Growth

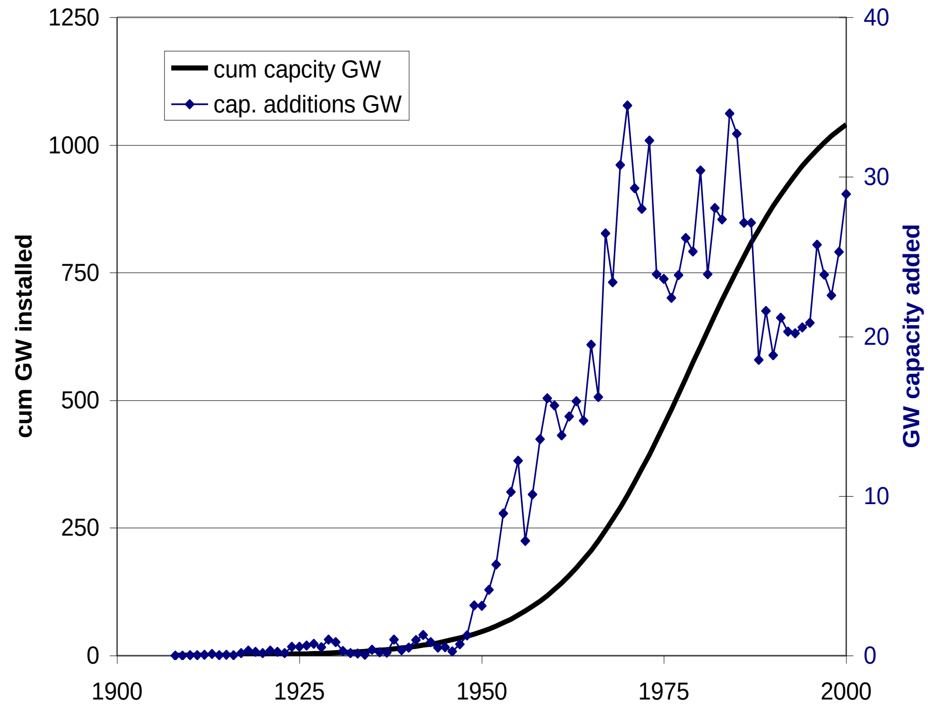
- Distinct phases:
  Long experimentation (3 decades) at small unit scale before successful scale-up
- Market size and growth periods related:
  big hits require time (many decades)
- Advantages of late-adopters:
  learning and acceleration, but need integration into knowledge networks

5 Phases in Scaling-up of a Technology:

Example Coal Power Plants (Source: C. Wilson, 2009)

3: build many (large) units





1: build many (small) units

4: scale-up industry

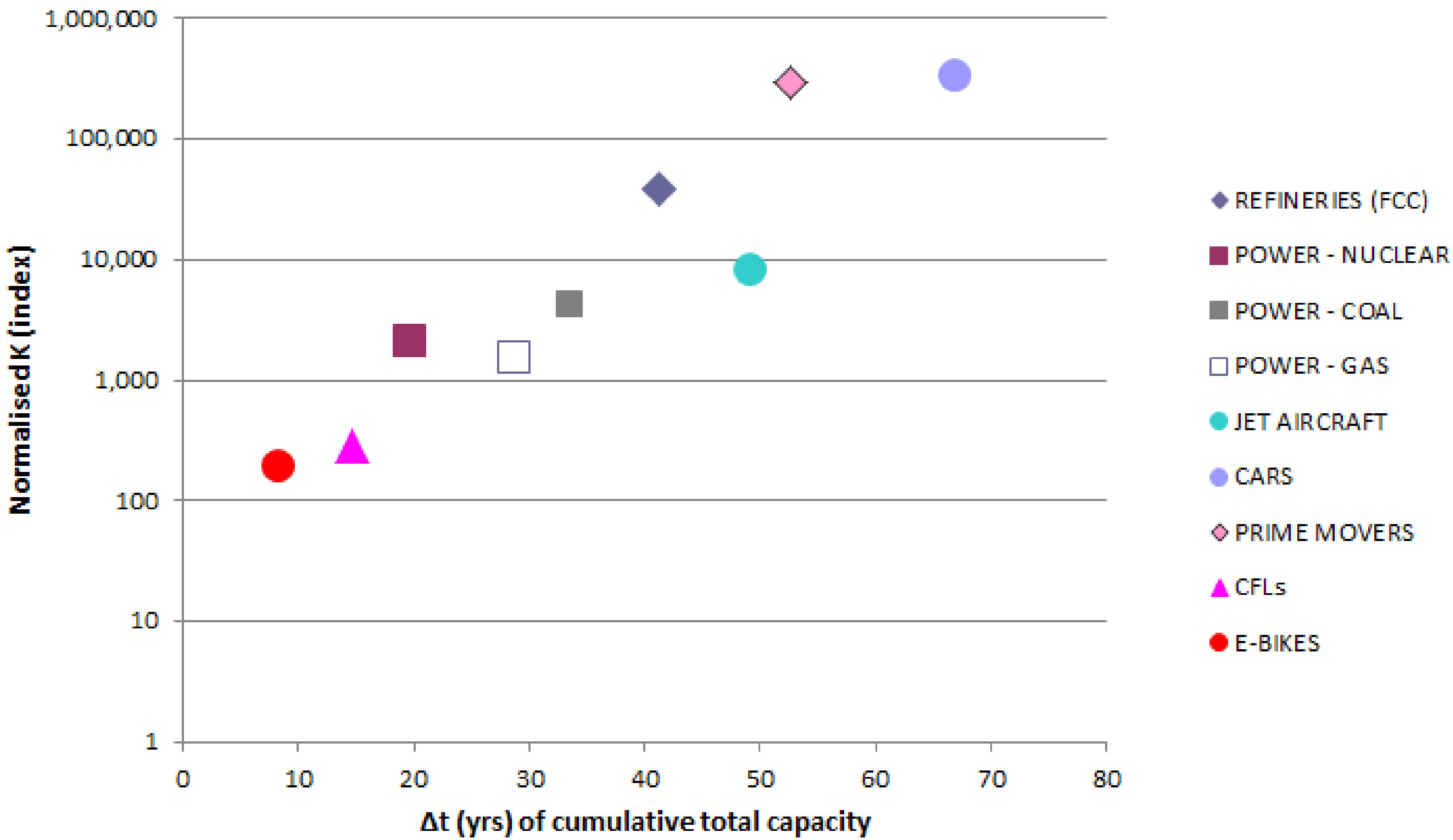
2: scale-up units:

2.1. at frontier

2.2. average

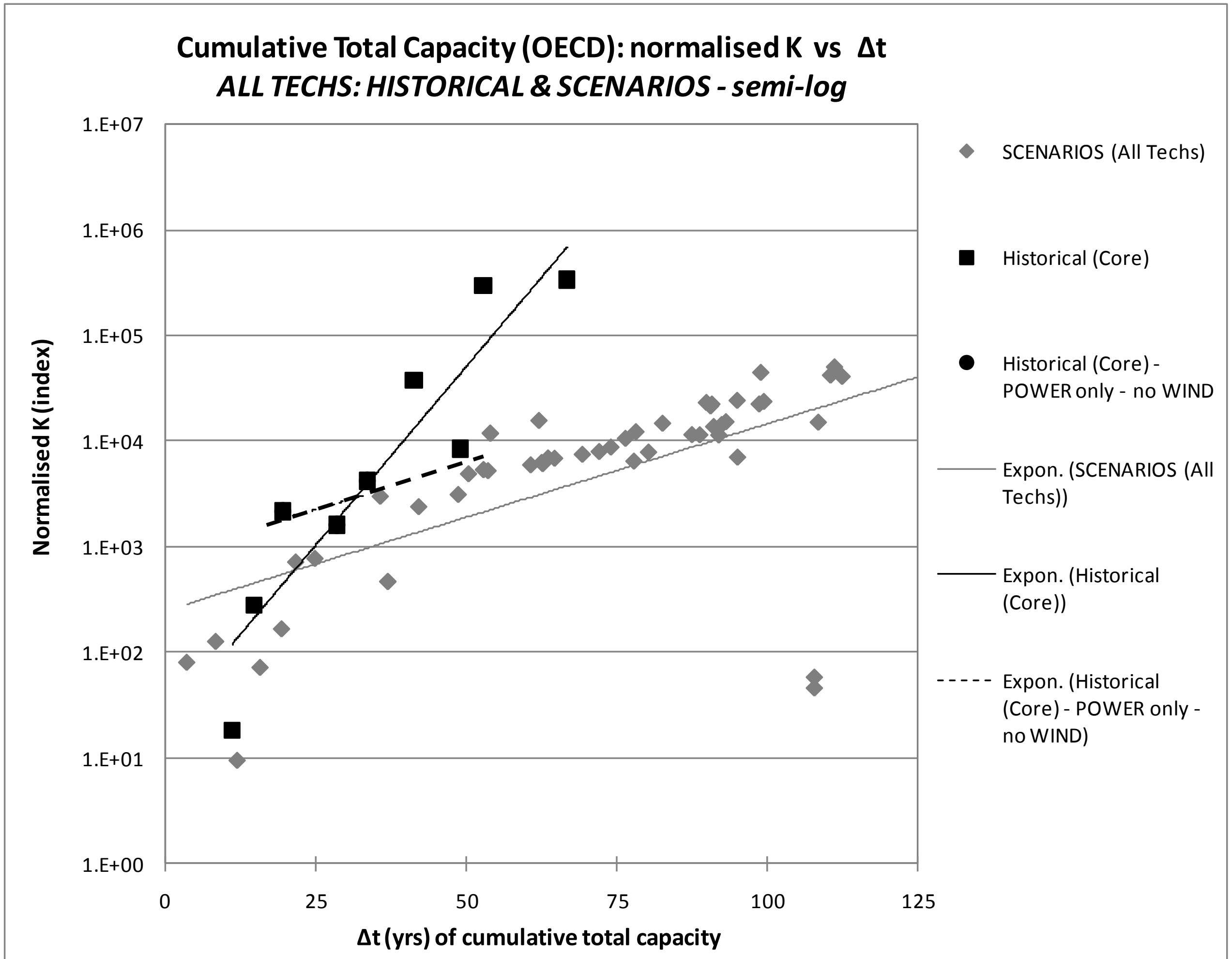
5: grow outside core markets
(globalize)

Market Size (normalized index) vs Diffusion Speed (Δt) of Energy Technologies



Source: C. Wilson, 2009, e-bikes courtesy of Nuno Bento, IIASA, 2011

Scaling patterns Past and Scenarios (GGI)
(8 Scenarios: A2r/B1/B2 * base/670/480)

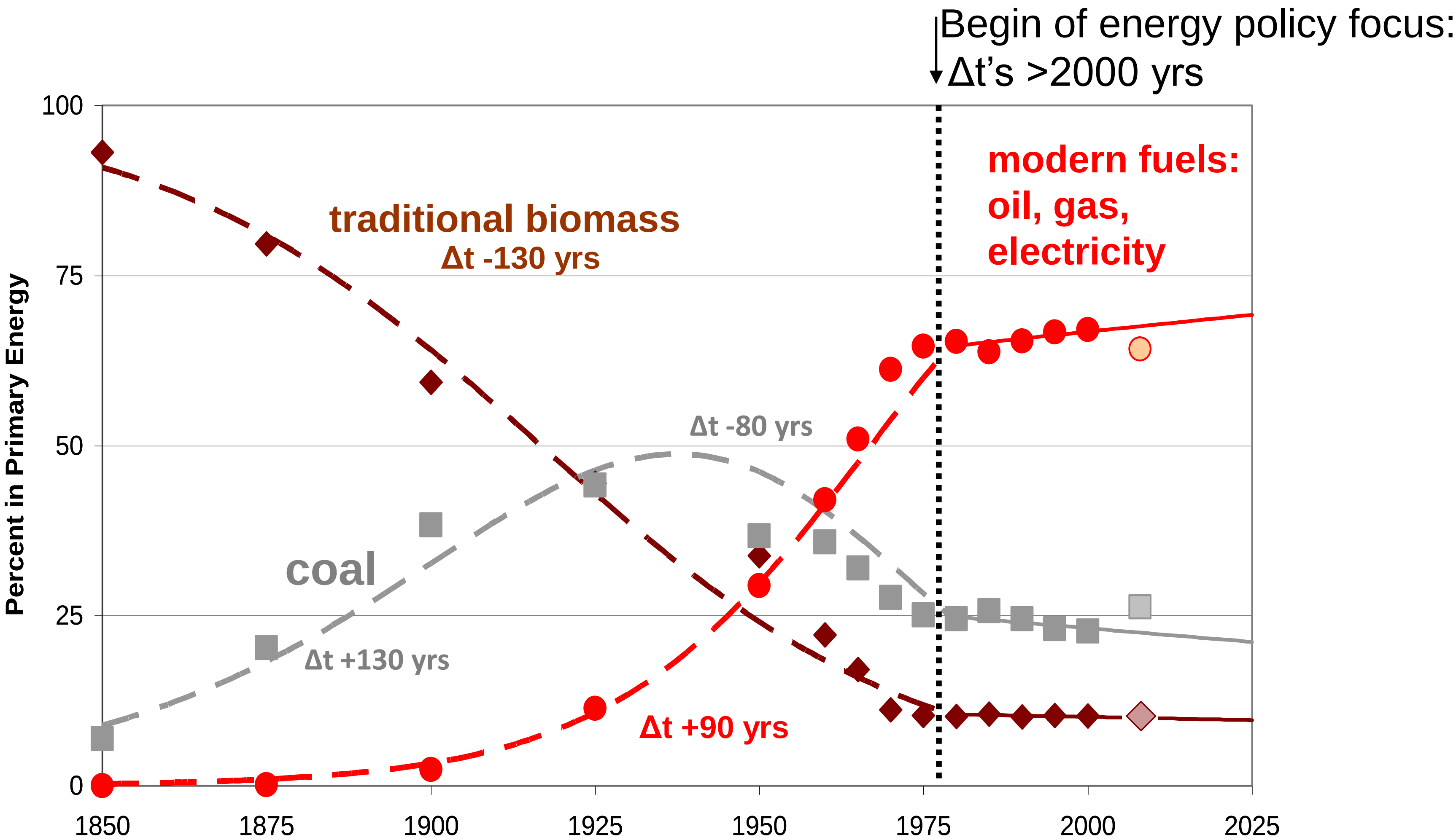


- Scenarios are more conservative as durations (and extents) increase
- Again: closer relationship just for power techs historically
  - *dotted black line*

Mixed Impact of Policies

- Significant “de-acceleration” since 1970s (inconsistent policy “push and pull”)
- Success stories when policies are:
  aligned, patient, systemic, and dynamic
  e.g. Japan, Brazil vs. US
- Systemic underinvestment in end-use and efficiency: ALL actors
- ETIS increasingly global, but too few international tech cooperation

World – Historic Primary Energy Transitions (changeover time Δt: 80-130 years)



Source: GEA KM24, 2011