Wissenschaftlicher Beirat für Globale Umweltfragen (WBGU)

Innovation as Driver of Global Transformations. Inputs to the WBGU “Transformations” Study

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Questions Asked

- What are the preconditions for radical innovations (technological, social) and for technology leaps?
- How can innovation processes, meant to support the transformation towards a low-carbon society, be steered and accelerated?
- How can the radical innovations which are necessary for a global low-carbon society be diffused globally?
- Which fields of innovation do you think are the most important ones for a transformation towards a low-carbon society?
- Bonus: Historical Diffusion/Transition patterns: what do we know?

A Brief History of PV

1839: Becquerel discovers photovoltaic effect.

1904: Hallwachs discovers that copper-cuprous oxide mix is photosensitive. Einstein publishes paper on the photoelectric effect.

1918: Czochralski grows first single-crystal silicon.

1923: Albert Einstein receives Nobel Prize for explaining effect.

1957: "Solar Energy Converting Apparatus" patent issued to AT&T.

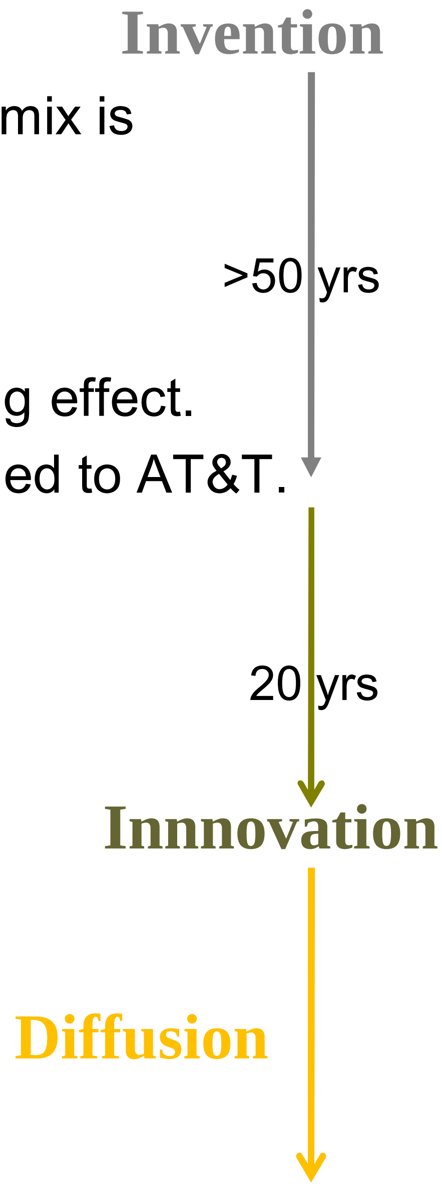
1958: Vanguard I: first PV-powered satellite.

1963: Japan installs the world’s largest PV unit (0.2 kW!) in lighthouse.

1974: MITI initiates Sunshine Project.

1977: PV manufacturing exceeds 0.5 MW/yr:

2007: Global installed PV capacity: ~10 GW
capacity additions 2007: 2.5 GW



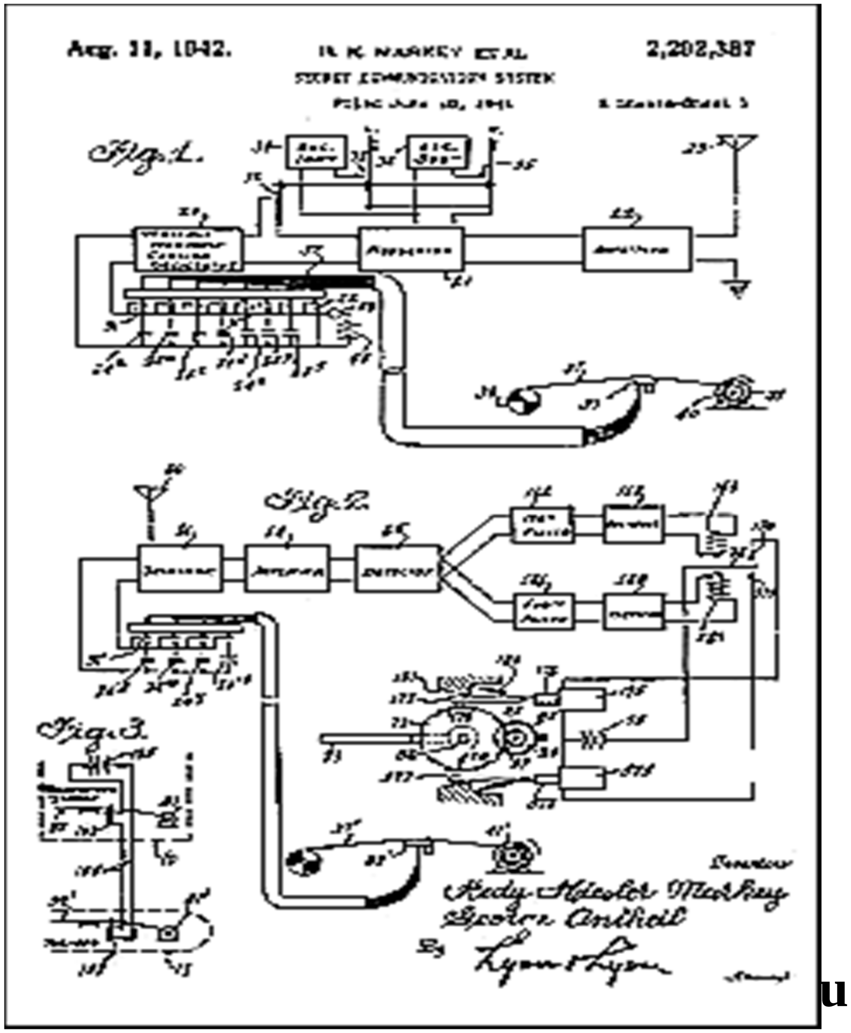
Note: Science→Technology (current paradigm)
BUT: Technology →Science (frequent in history)

Q1: Preconditions for radical innovations

- TC is evolutionary, i.e. has emergent properties. Impossible to define “radical” ex ante (even ex post, cf. Mensch/Kleinknecht controversy)
- 3 views:
  -- “breakthroughs” are serendipitous
  -- created via crisis of old: Schumpeter’s “gales of creative destruction” (AG)→ need for destruction mechanisms (and not dominant “grandfathering”)
  -- planned/mastered (Manhattan and Apollo project models; true for innovation but very costly, no ensuing diffusion)
- Q: is “radical” innovation needed at all (e.g. fusion)?
  Perhaps simply need acceleration of diffusion of known (and to be improved) practices/technologies
  (PV, CCS, and above all efficiency!)
  (ex. Alphabetization of USSR in 1920s, cell phones in DCs)
- Q: is “radical” innovation not coming too late?
  (invention-innovation lags, diffusion time,..)

Invention – Innovation Lag: The Unrecognized Inventor

Movie Actress Hedy Lamarr (Eva Kiesler) together with musician George Antheil patented “secret communication system” in 1942 which US Navy thought useless
Now as “spread spectrum technology” basis of all cell phones.
Invention-Innovation lag: 50 years!



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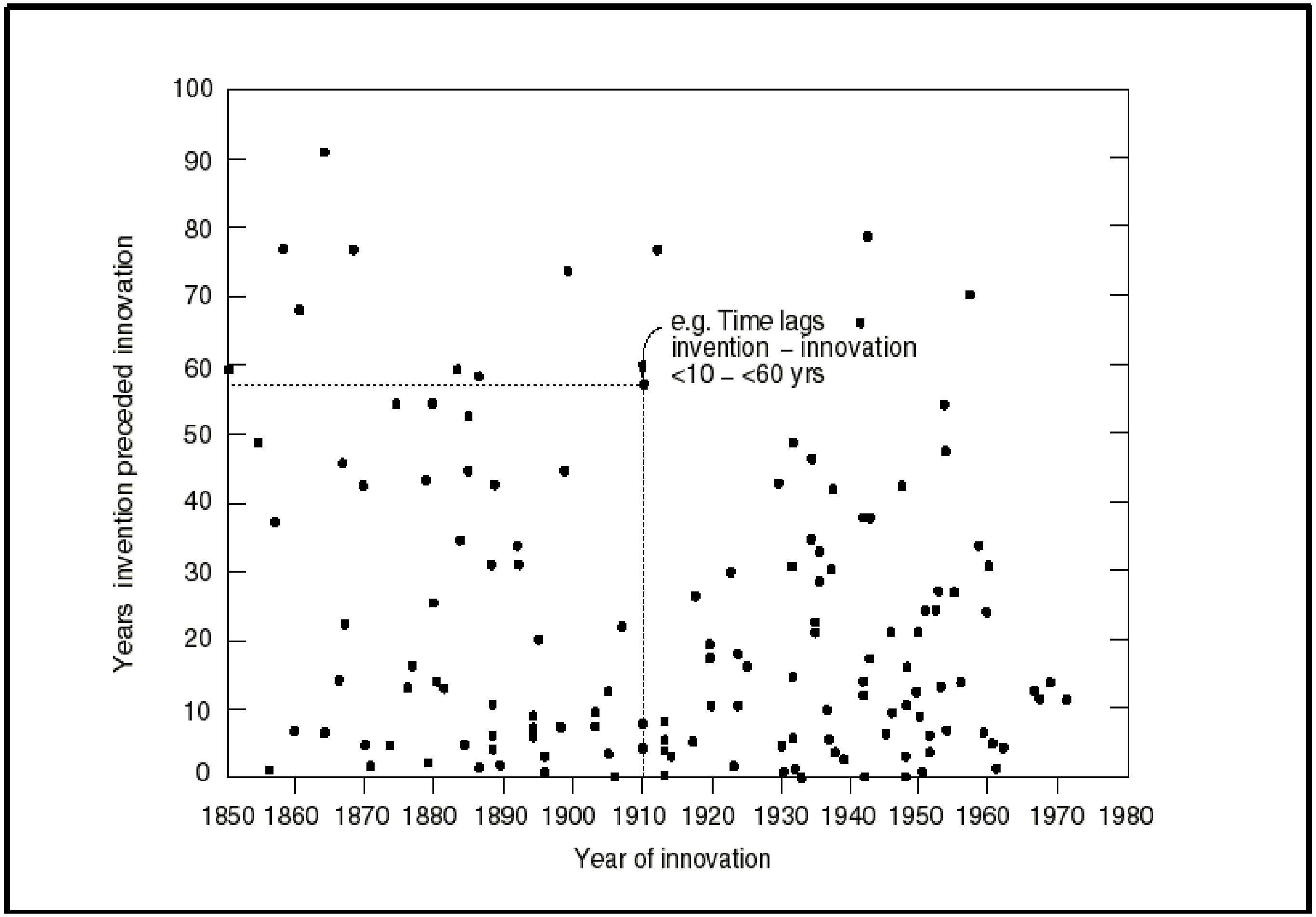
Time Lag Between Invention and Innovation: No shortening of stochastic variation

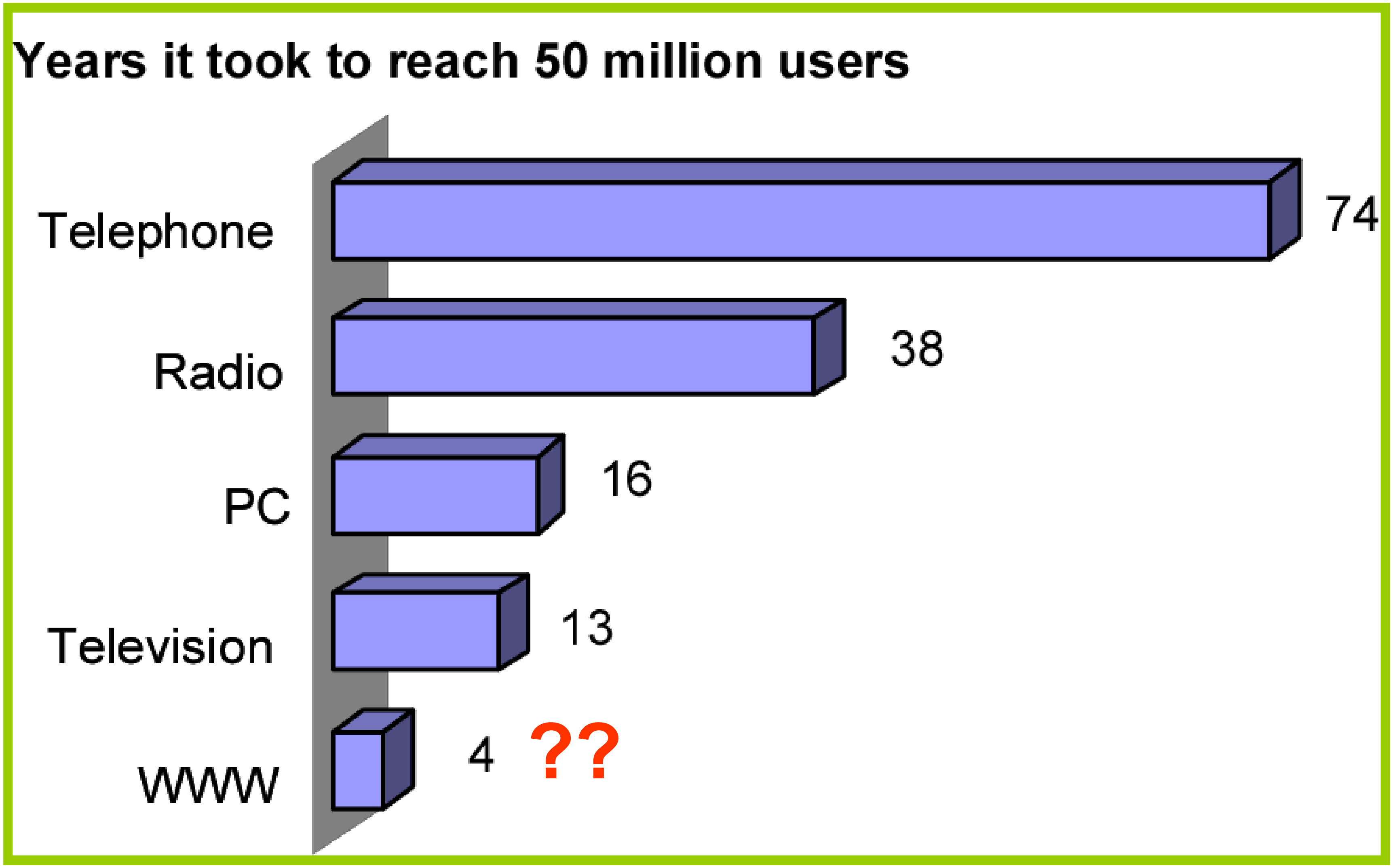


Source: Rosegger, 1996

Q2: Steering/accelerating innovation

- No production function for innovation known (only minimum but not-sufficient conditions) inputs: $$$, human capital, incentive structures, structured collective learning channels (user-supplier links)
- more inputs ≠ more outputs
- policy pitfalls: →GEA KM24 “policy quality list”
- Accelerating <u>diffusion of innovations</u>:
  see Q3

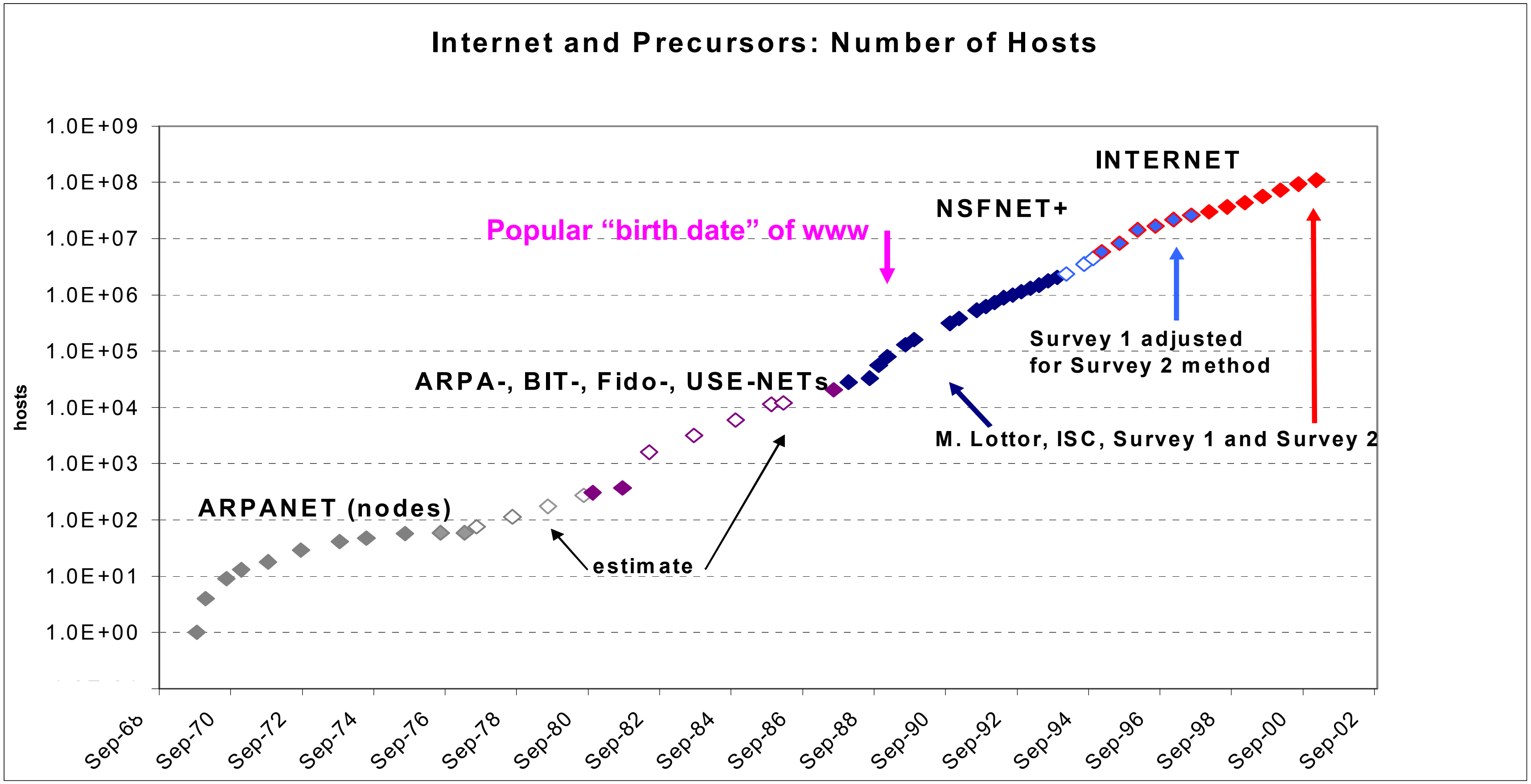
The Conventional View: Accelerating Change



http://www.un.org/cyberschoolbus/briefing/technology/tech.pdf

Growth of the Internet:

25 years as public (military/academic) infrastructure before commercialization!



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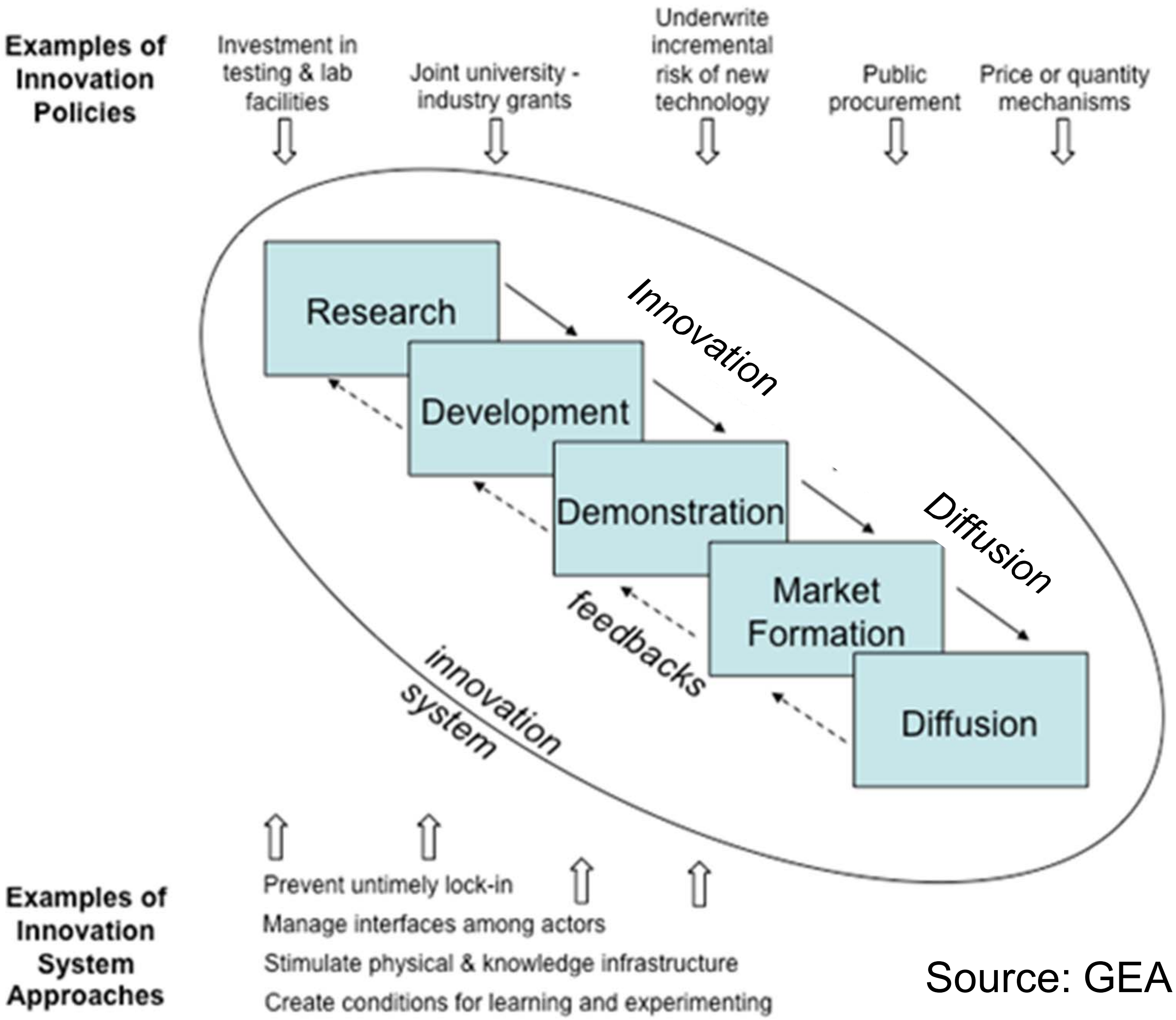
Technology Genesis - Concepts and Policy Leverages



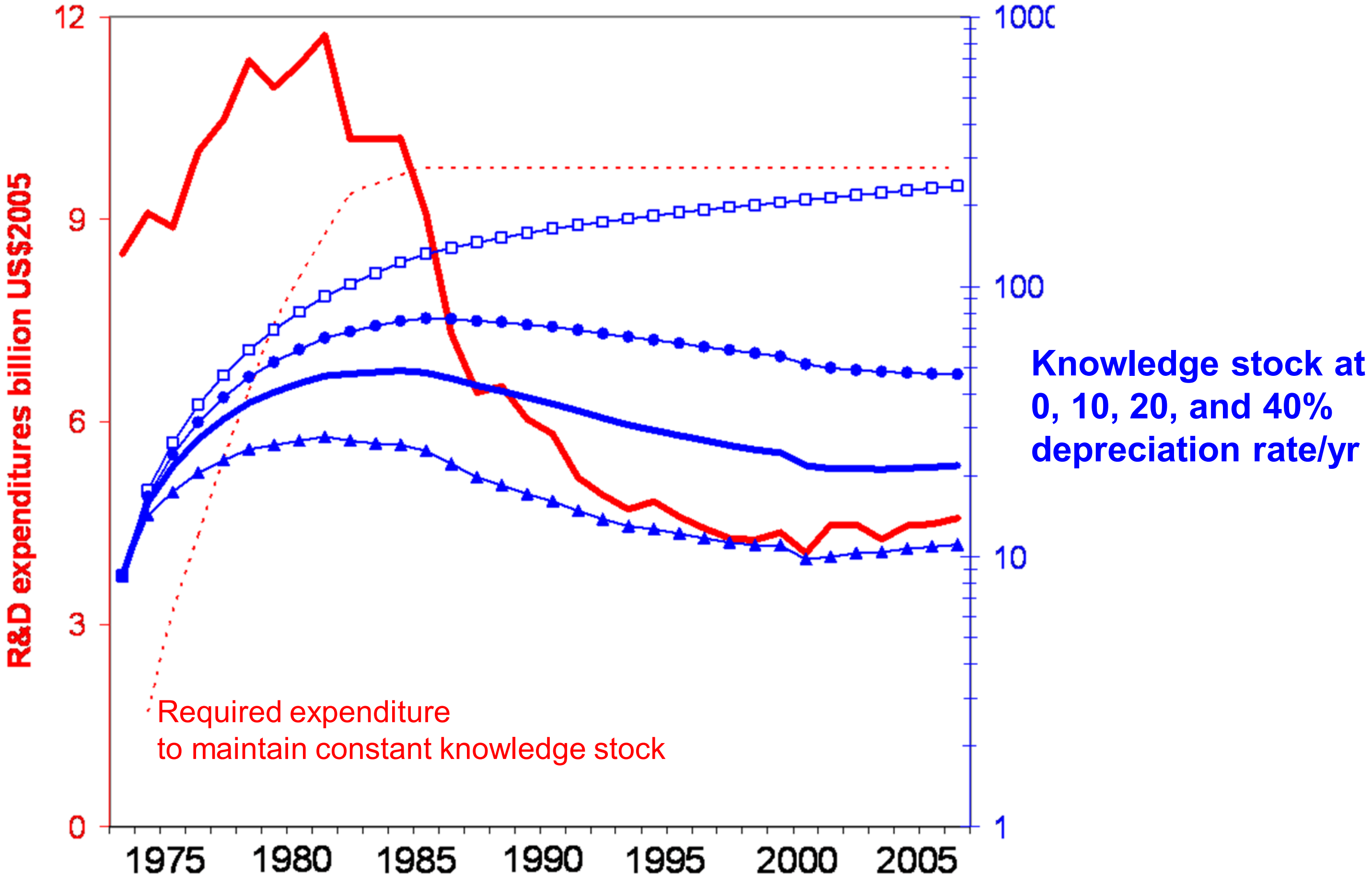
Source: GEA KM24 draft

Characteristics of Successful Technology Innovation Policies

- Create Knowledge! Or: Enable technological learning while learning about technologies yourself
- Assure Feed-backs! Or: Create/enable knowledge flows for technology learning and spillovers.
- Experiment! Or: Stop worrying about failure.
- Align Incentive Structures! Or: Don't confuse the market.
- Be stable! Or: Innovation relies on policy stability and credibility.
- Focus of Technology Portfolios! Or: don't pick a winner, but be picky on your picks.

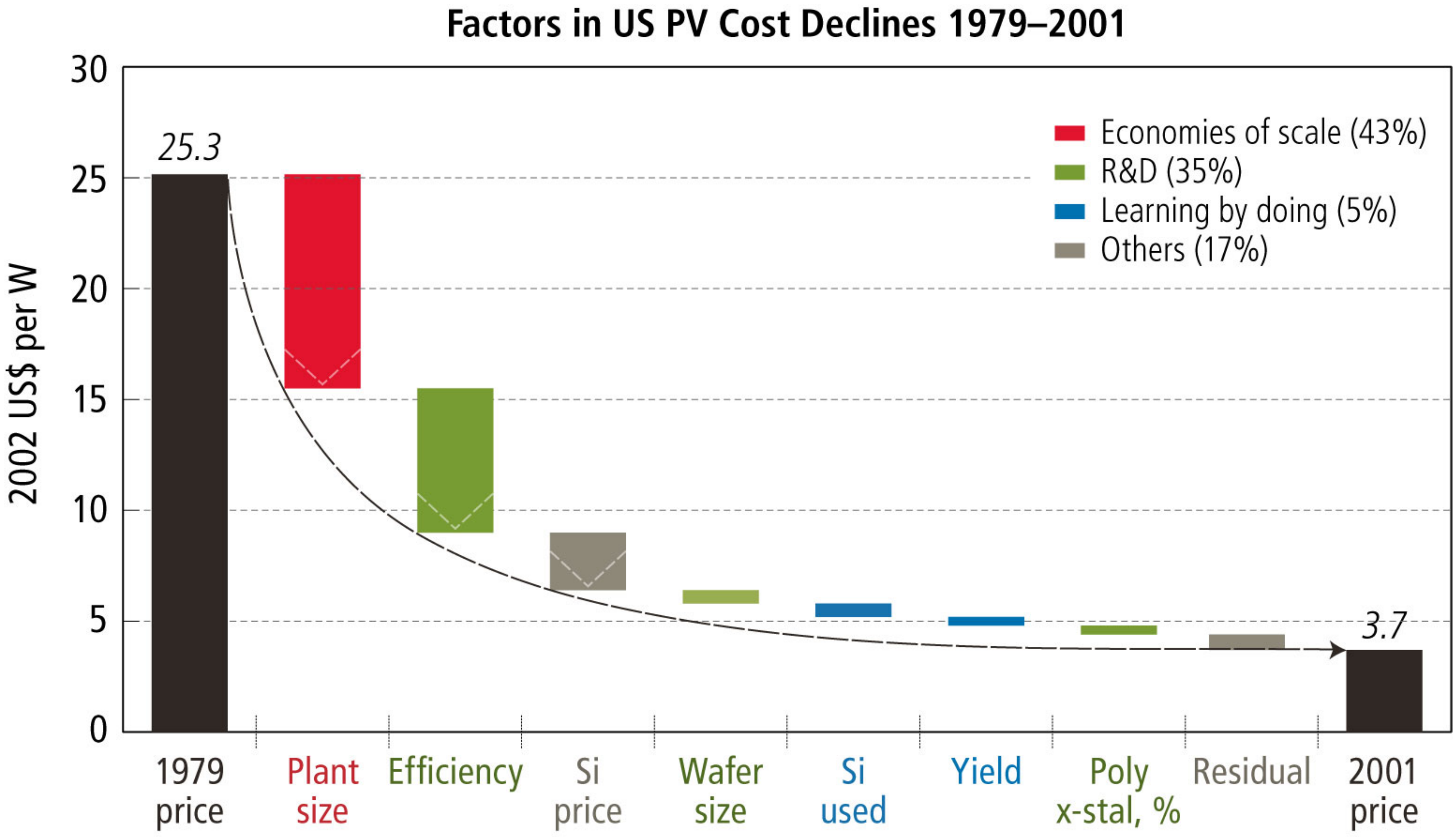
Source: GEA KM24 draft

Nuclear R&D Expenditure vs. remaining Knowledge Stock
(knowledge obsolescence)



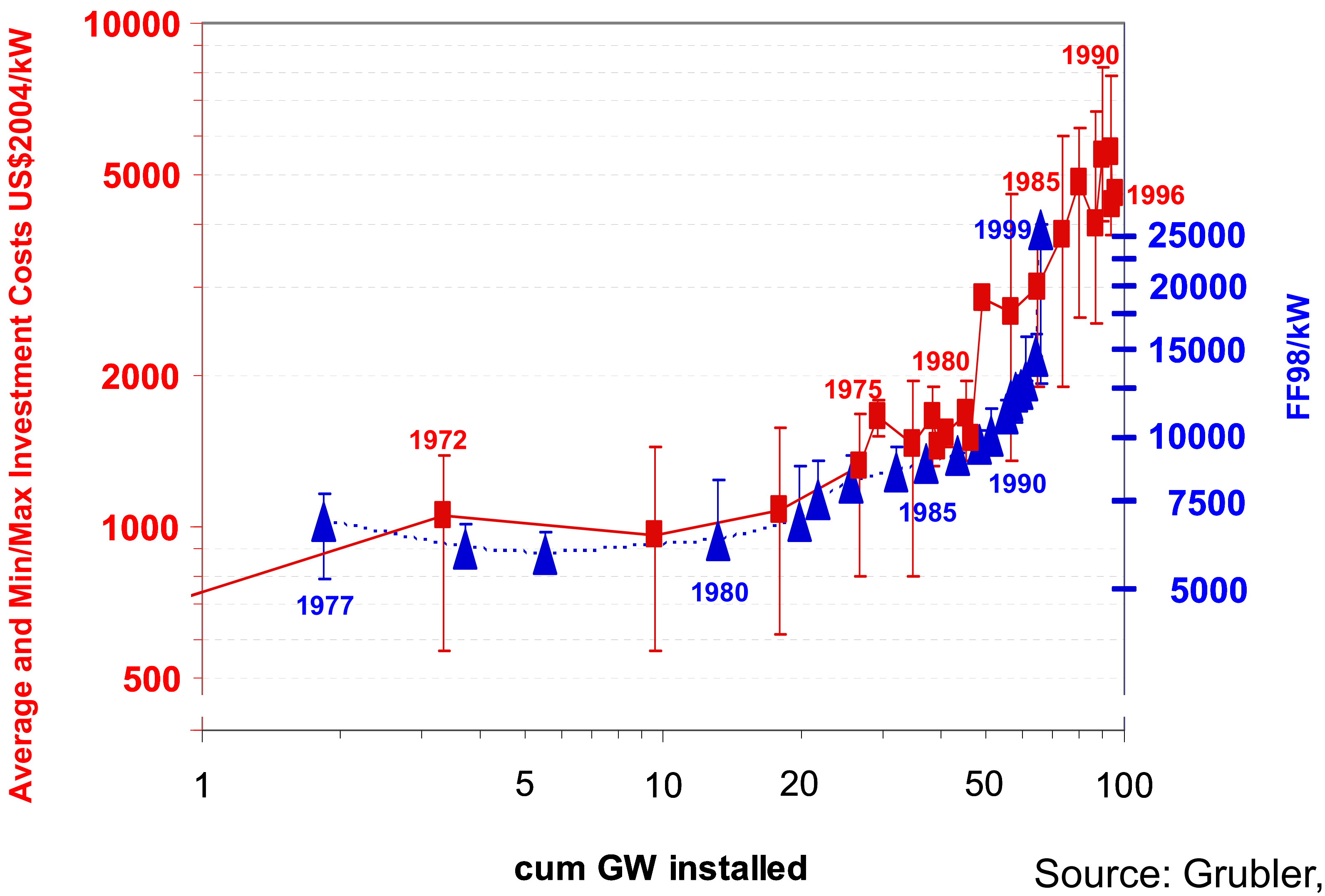
Data: IEA, 2009 energy R&D stats. Totals for all IEA countries. Source: GEA KM24 draft

Multiple Sources of Technology Learning



Source: G. Nemet, 2008

Nuclear Investment Costs in US and France: 2 Cases of Negative Learning



Source: Grubler, 2010

Q3: How to diffuse radical solutions globally?

- good knowledge of diffusion drivers at micro level,
  but serious constraints at macro-level (systems size,
  techn. interdependence) →Table_EnePolicy
- Key concept: diffusion depends on:
  -- innovation characteristics (Passivhaus)
  -- adoption environment characteristics (building
  standards, energy/carbon prices)
  which are <u>not substitutable</u>
  (CCS in China w/o carbon price??)
- Globalization not via imitation but due to need
  to escape network exclusion (ex Internet)
- Core periphery: lags, catch-up, and heterogeneous
  adoption levels

Diffusion: Macro variables

- Involves time and space (S-curve and spatial hierarchy centers)
- First mover vs. follower: longest (slowest) diffusion time & highest adoption (first mover) vs. catch-up at lower levels (follower)
- Market size vs speed and impact:

  Large size & impact = slower diffusion

  Small size and impact (fashion) = fast diffusion
- Diffusion (slower) vs. substitution (faster)

Determinants of Diffusion Speed (beyond macro)

- Type of adoption decision (individual, collective, authoritative)
- Type of communication channels (mass media vs. word-of-mouth)
- Nature of social system (interconnection, sources of learning: internal vs. external)
- Existence and efforts of change agents

:

-- relative advantage (e.g. performance, costs);

-- adoption effort (e.g. investment size);

-- compatibility (technological, social integration);

-- observability (social visibility, learn from neighbors);

-- trialability (learning from own experience).

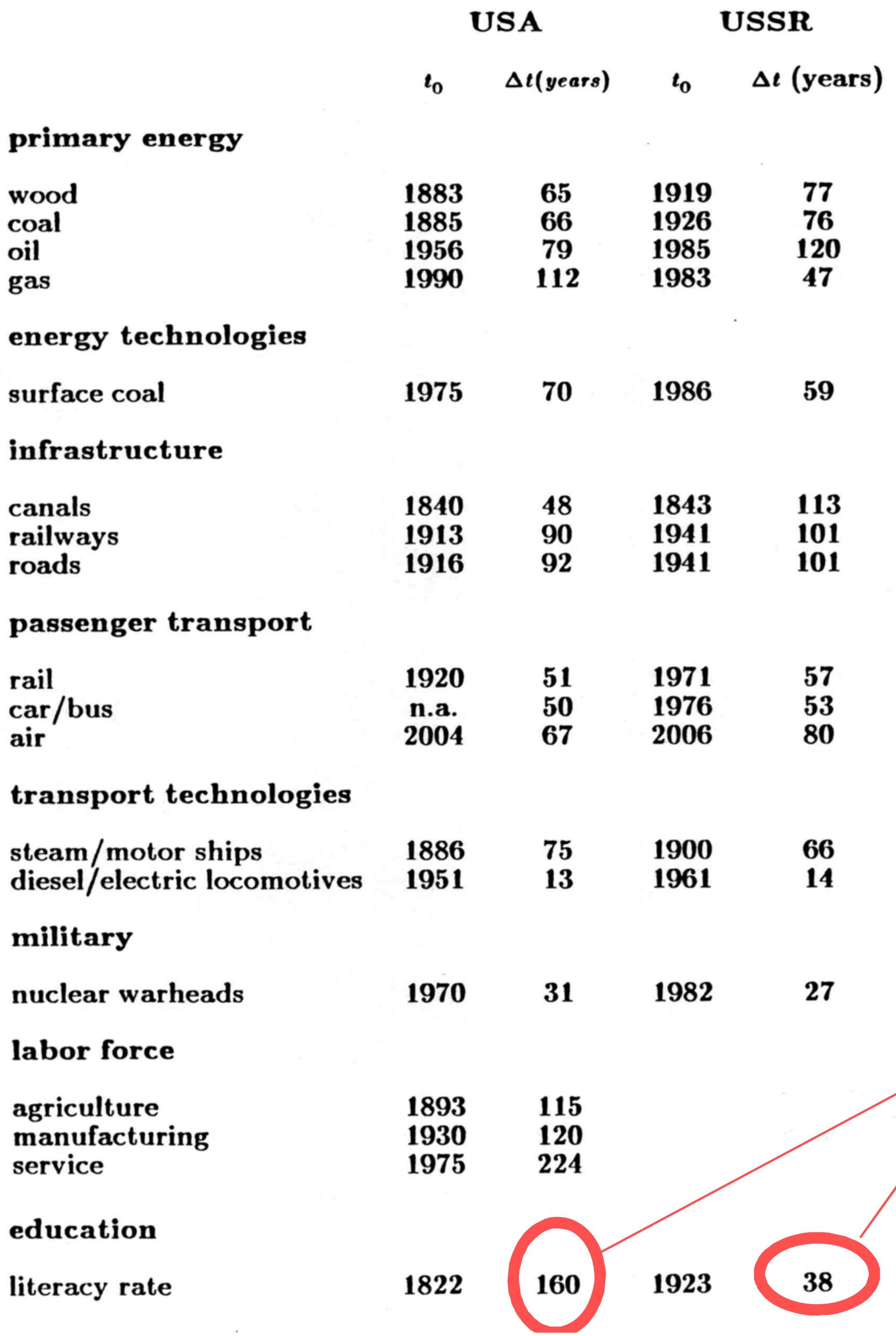
Rates of Change:
(Diffusion Rates of Transport Systems)

	USA		USSR	
	t_0	Δt	t_0	Δt
Total length of transport infrastructure	1950	80	1980	80
Growth of railways				
1830-1930	1858	54	1890	37
1930-1987	Decline	Decline	1949	44
Treated ties (USA)	1923	26		
Track electrification (USSR)			1965	27
Replacement of steam locomotives	1950	12	1960	13

t_o = diffusion midpoint (50% completion rate)
Δt = diffusion rate (years to grow from 10% to 90%)

Source: Grubler, 1998

Diffusion/Substitution Rates and Timing US - USSR



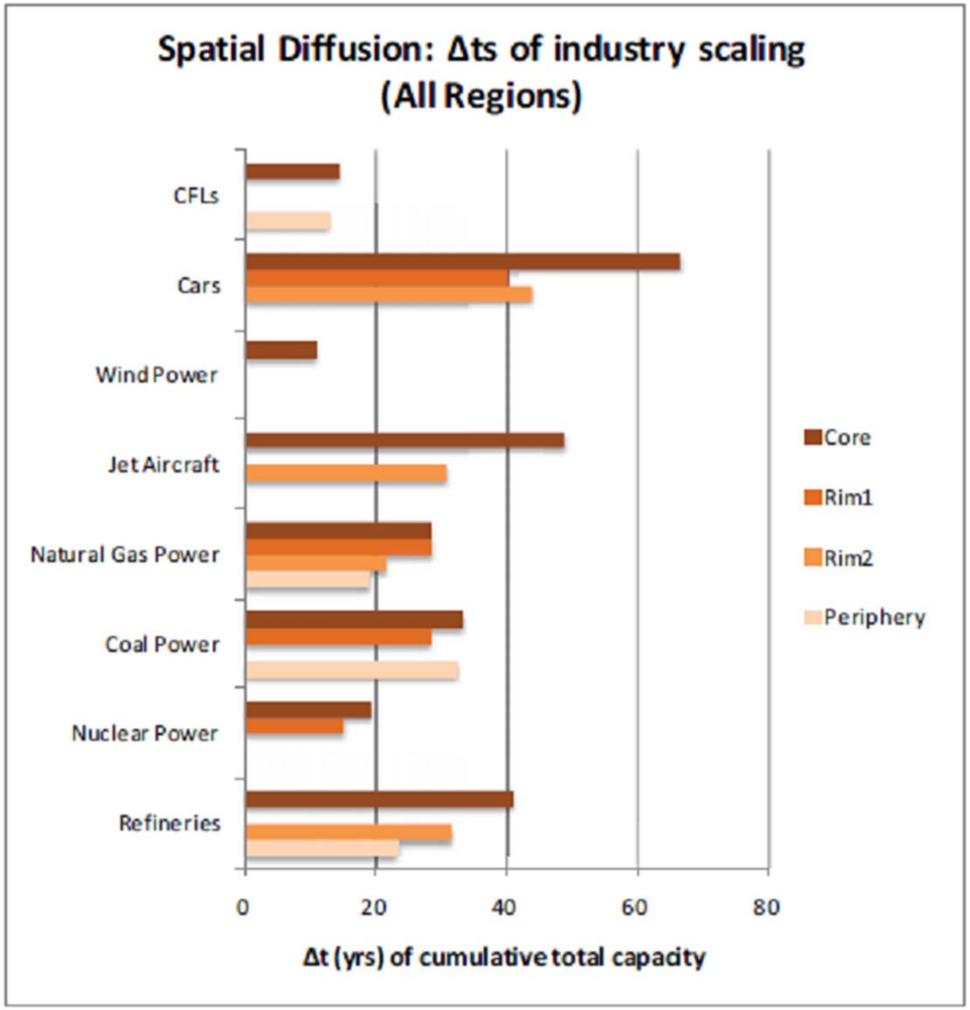
	USA		USSR	
	t_0	Δt(years)	t_0	Δt (years)
primary energy				
wood	1883	65	1919	77
coal	1885	66	1926	76
oil	1956	79	1985	120
gas	1990	112	1983	47
energy technologies				
surface coal	1975	70	1986	59
infrastructure				
canals	1840	48	1843	113
railways	1913	90	1941	101
roads	1916	92	1941	101
passenger transport				
rail	1920	51	1971	57
car/bus	n.a.	50	1976	53
air	2004	67	2006	80
transport technologies				
steam/motor ships	1886	75	1900	66
diesel/electric locomotives	1951	13	1961	14
military				
nuclear warheads	1970	31	1982	27
labor force				
agriculture	1893	115		
manufacturing	1930	120		
service	1975	224		
education				
literacy rate	1822	160	1923	38

Note similarities despite fundamental different diffusion environment: Central Planning vs. Market

Biggest Difference:
Social "technologies"

Source: Adapted from Grubler, 1990

Technology Diffusion Dynamics (Δt) from Core to Rim and Periphery



Source: C. Wilson, 2009.

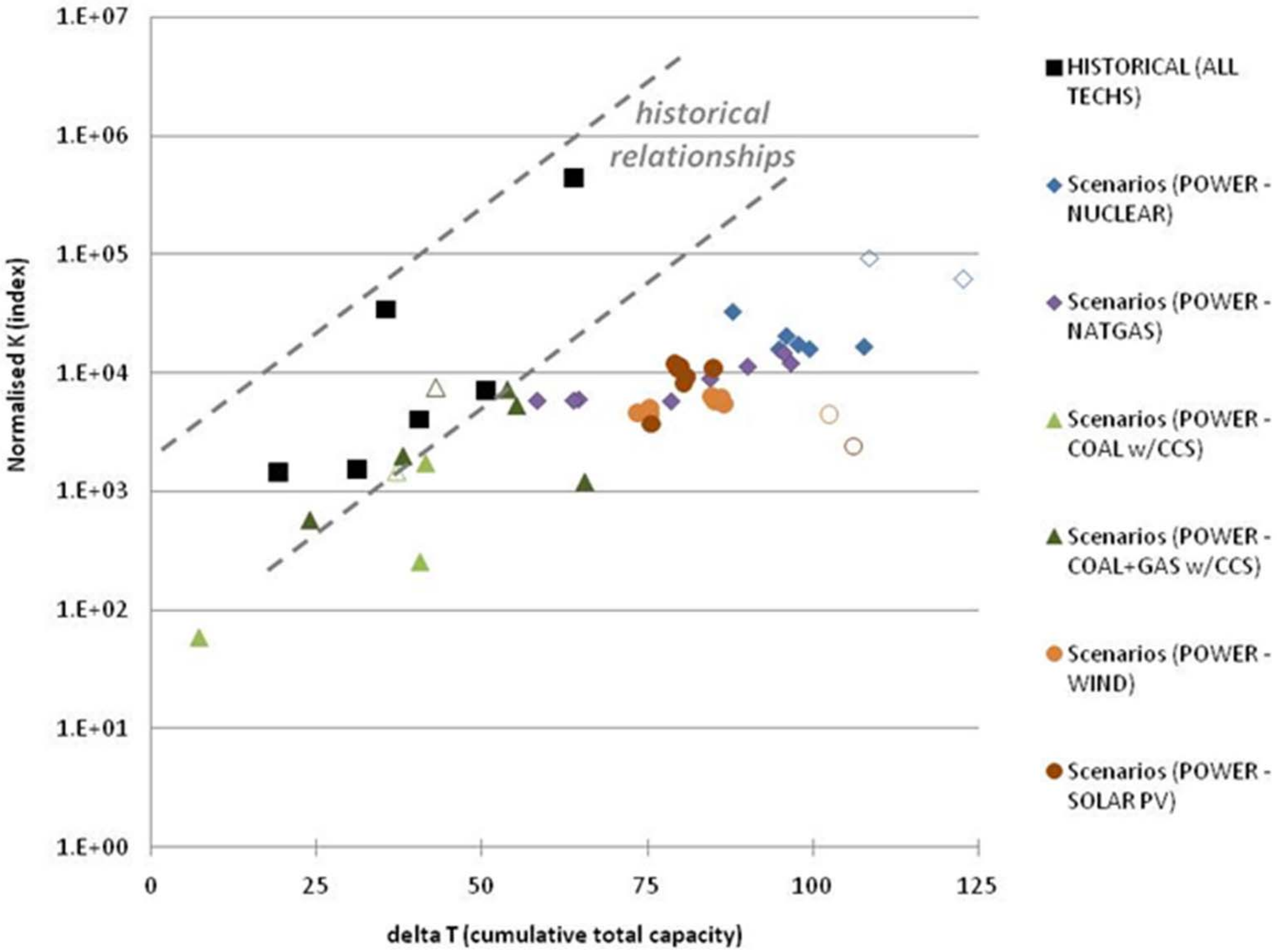
Explaining Differences in Diffusion Speed

(each additional o implies *ceteris paribus* slower diffusion, each additional + implies *c.p.* faster diffusion)

Δt	**Example**	**Adoption Effort High (D) Low (S)**	**Rel. Advantage**	**Market Size (Scale)**	**Complexity**	
					Infra-structure needs	**technol. Interde-pendence**
80/**110**	coal vs wood USA/**World**	S	++	oo**o**	oo**o**	ooo
47/**60**	railways France/**World**	D	+++	oo**o**	oo	ooo
25	% US homes with radio	D	++	oo	o	oo
28	mechanization coal mines Russia	S	+	o	o	oo
16	Car vs. horse, France, UK	S	++	o	oo	o
15	Color vs. B/W TV, USA	S	+	o	o	o

Source: adapted/modified from Grubler/Nakicenovic/Victor, 1999, Energy Policy 27:247-280

Energy Technology Capacity Growth – Historical and in Global Scenarios (BLs+stabilization)



Source: C. Wilson, 2009.

Q4: Most important field for low-C society

- AG (and IA models/scenarios) view:
  efficiency, efficiency, efficiency
  end-use, end-use, end-use
  -- amplifies supply-side leverages
  -- granularity decreases innovation/financial risks
  -- co-benefits (pollution, security)
  -- free lunches possible

- BUT
  -- "inconvenient truth" against vested (supply) interests
  →energy R&D portfolio biases
  -- granular organizationally (=difficult to manage)
  →needs new institutions, business models (ESCOMs)
  -- cumulative process requires dynamic, cumulative targets/incentives (at odds w. political cycles)

Mitigation Portfolios (which technologies we need) *versus* R&D (which technologies we develop)

			All IEA countries			
	cumulative emission reduction 2000-2100 (mean of all scenarios)		cumulative R&D (1974-2007)		current R&D 2007	
	GtC	*%*	**10^9 US$2007**	*%*	10^9 US$2007	*%*
Energy efficiency	1662	*57.5*	38	*8.9*	1.6	*13.0*
Fossil Fuels	171	*5.9*	55	*12.8*	1.4	*11.3*
Renewables	537	*18.6*	37	*8.7*	1.5	*12.3*
Nuclear	269	*9.3*	236	*54.8*	4.6	*38.0*
Others	252	*8.7*	64	*14.8*	3.1	*25.4*
Total	**2890**	*100.0*	**431**	*100.0*	12.0	*100.0*

Source: Grubler&Riahi, 2010

Q5 (bonus): Historical Patterns of TC

- End use over supply
  -- main driver: new services (e.g. phone), vastly improved service efficiency (e.g. electric light vs. petroleum lamps, automobiles vs. horses (→Pearson)
  -- radical cost declines (multifarious!)
  -- granular rather than “lumpy”
- Innovation centers: urban
- Consistent scaling dynamics
  -- system size
  -- embeddedness in technology landscape
  -- Core – periphery

Energy Efficiency (%) and Emissions (g/km) for Horses, and Early and Contemporary Automobiles

	Horses	Cars (ca. 1920)	Cars (1995)
Engine efficiency, %	4	10	20
Wastes			
Solid	400	–	–
Liquid	200	–	–
Gaseous, including			
Carbon (CO_2)[d]	170	120	70
Carbon (CO)	–	90	2
Nitrogen (NO_x)	–	4	0.2
Hydrocarbons	2[e]	15	0.2

[d] Total carbon content of fuel

[e] Methane

Grubler, 1998

Capacity of US Energy Conversion Technologies

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

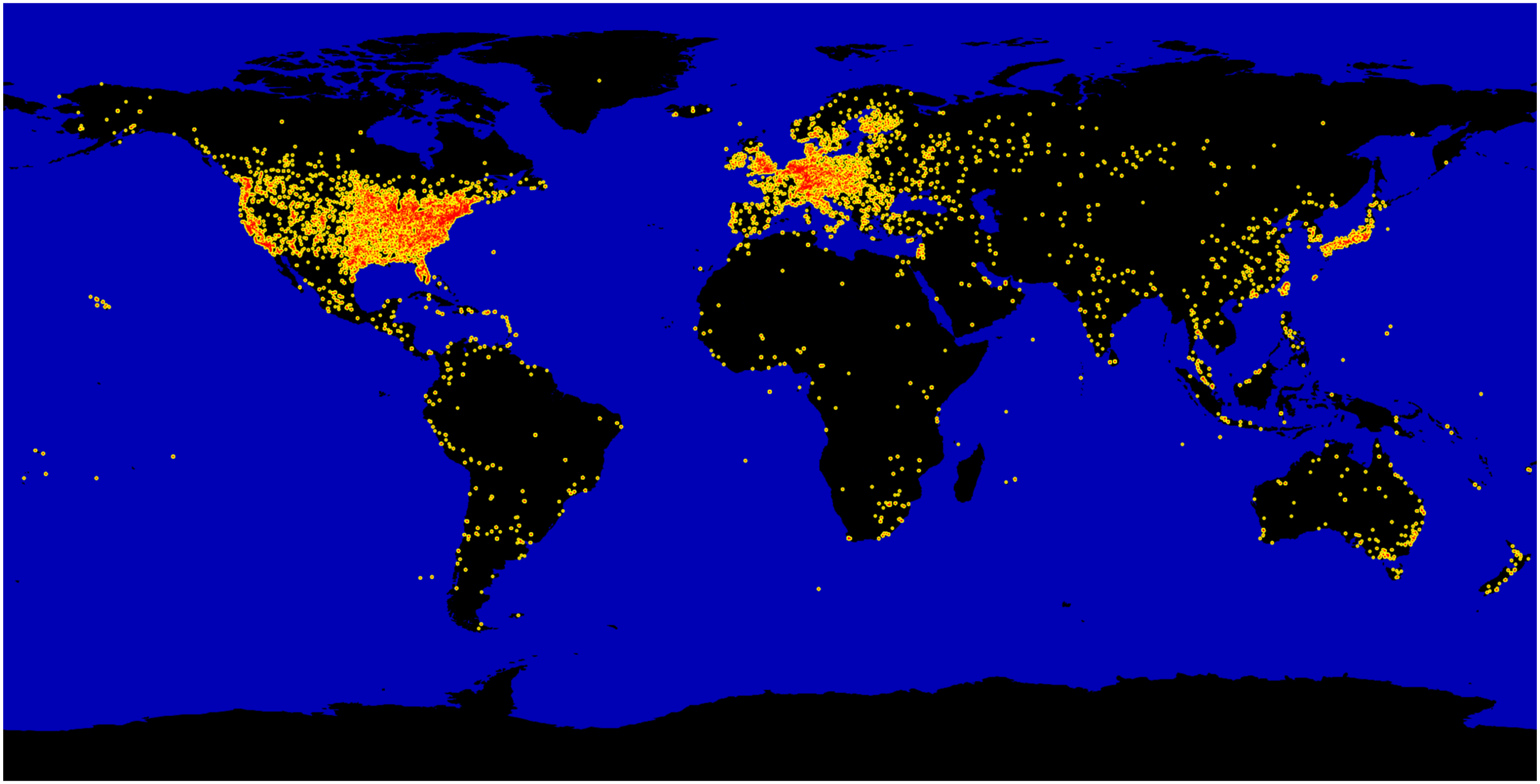
Energy end-use = 30 TW or 87% of all energy conversion technologies
= 5 TW or 50% when excluding automobiles

Source: GEA KM24, 2012

Internet Router Density

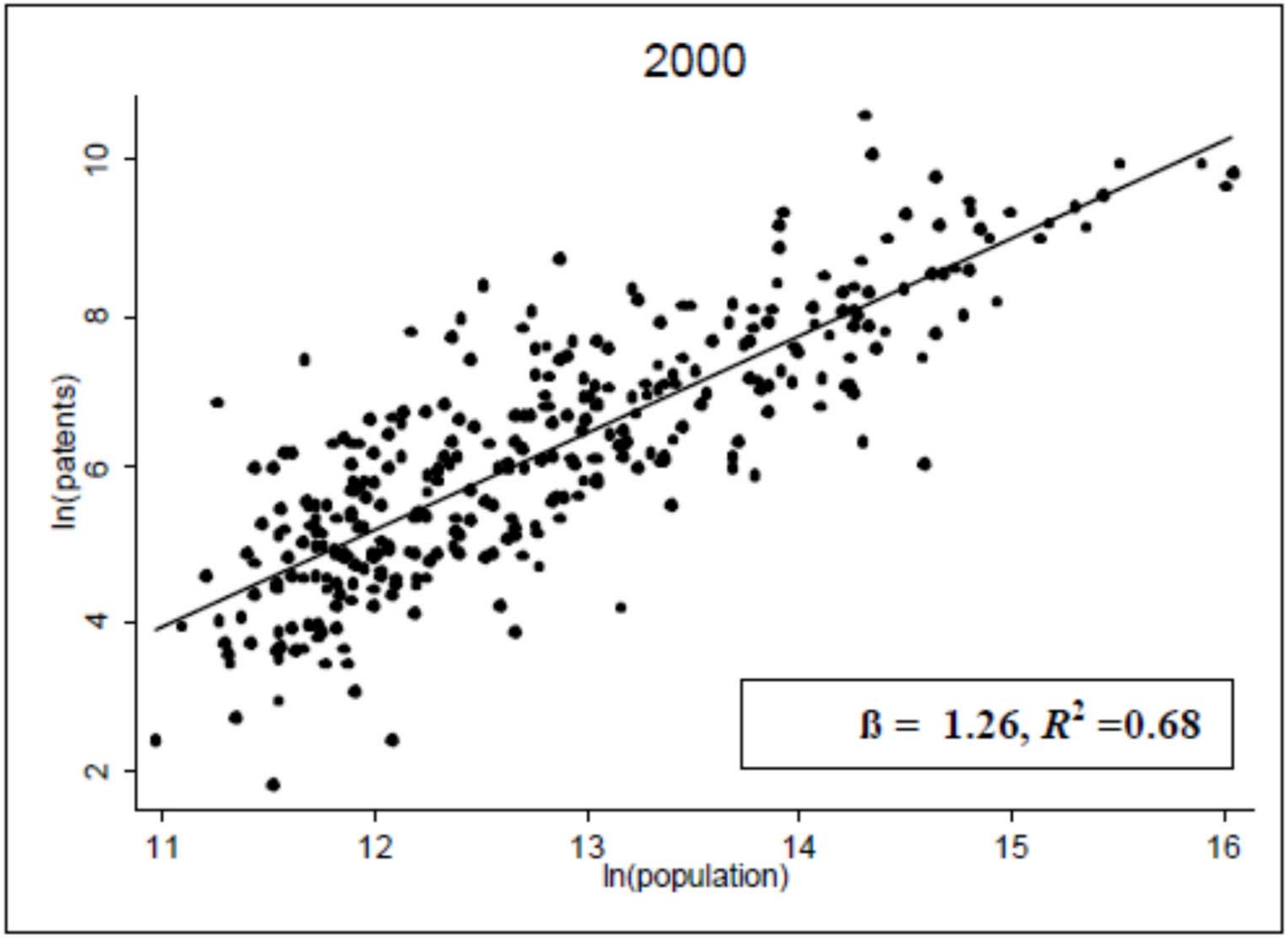
(sample of 564,521 routers)

Data: Mark Crovella, Boston University, 2007



96% of all internet routers globally are located in cities!
= highest urban concentration of all indicators reviewed. Source: GEA KM18 draft

Urban Scale and Inventive Activity (patents)
331 MSA in the US

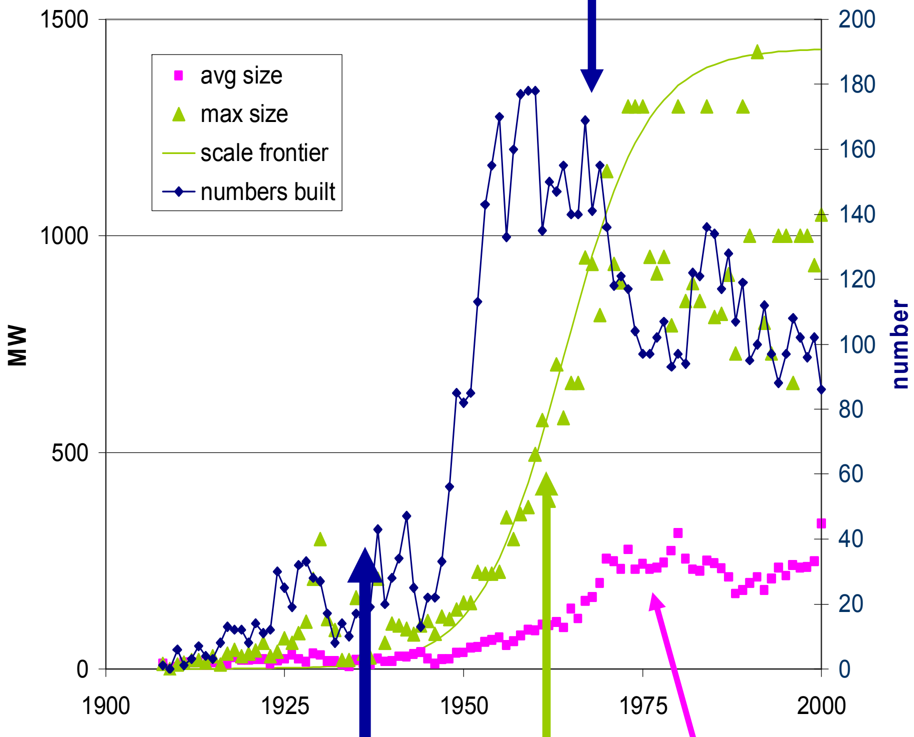


Source: Bettencourt, Lobo & Strumsky, 2004, SFI WP 04-12-038

5 Phases in Scaling-up a Technology:

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

3: build many (large) units

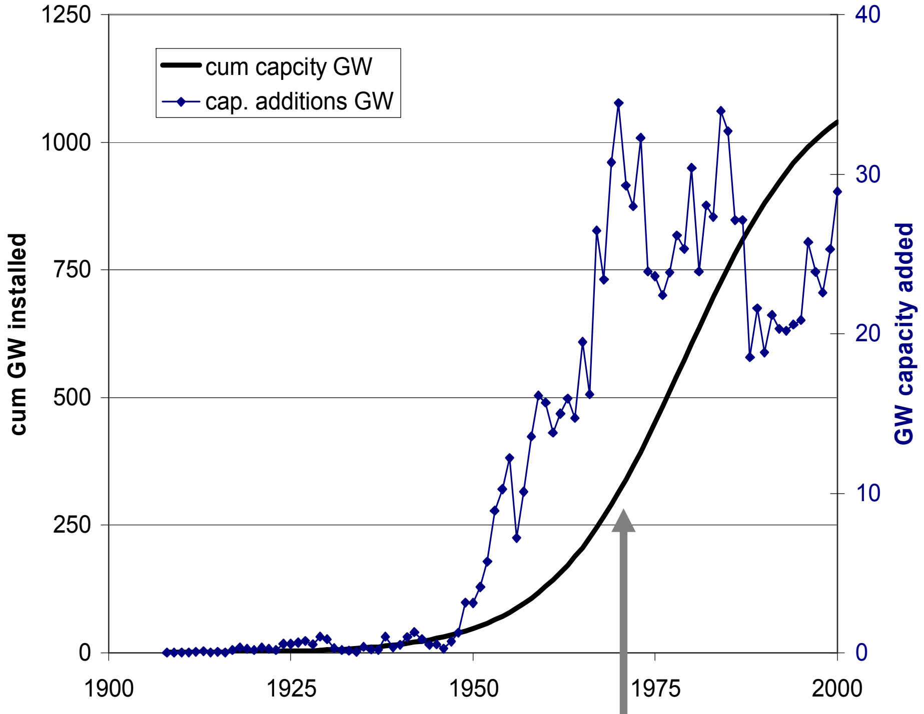


1: build many (small) units

2: scale-up units:

2.1. at frontier

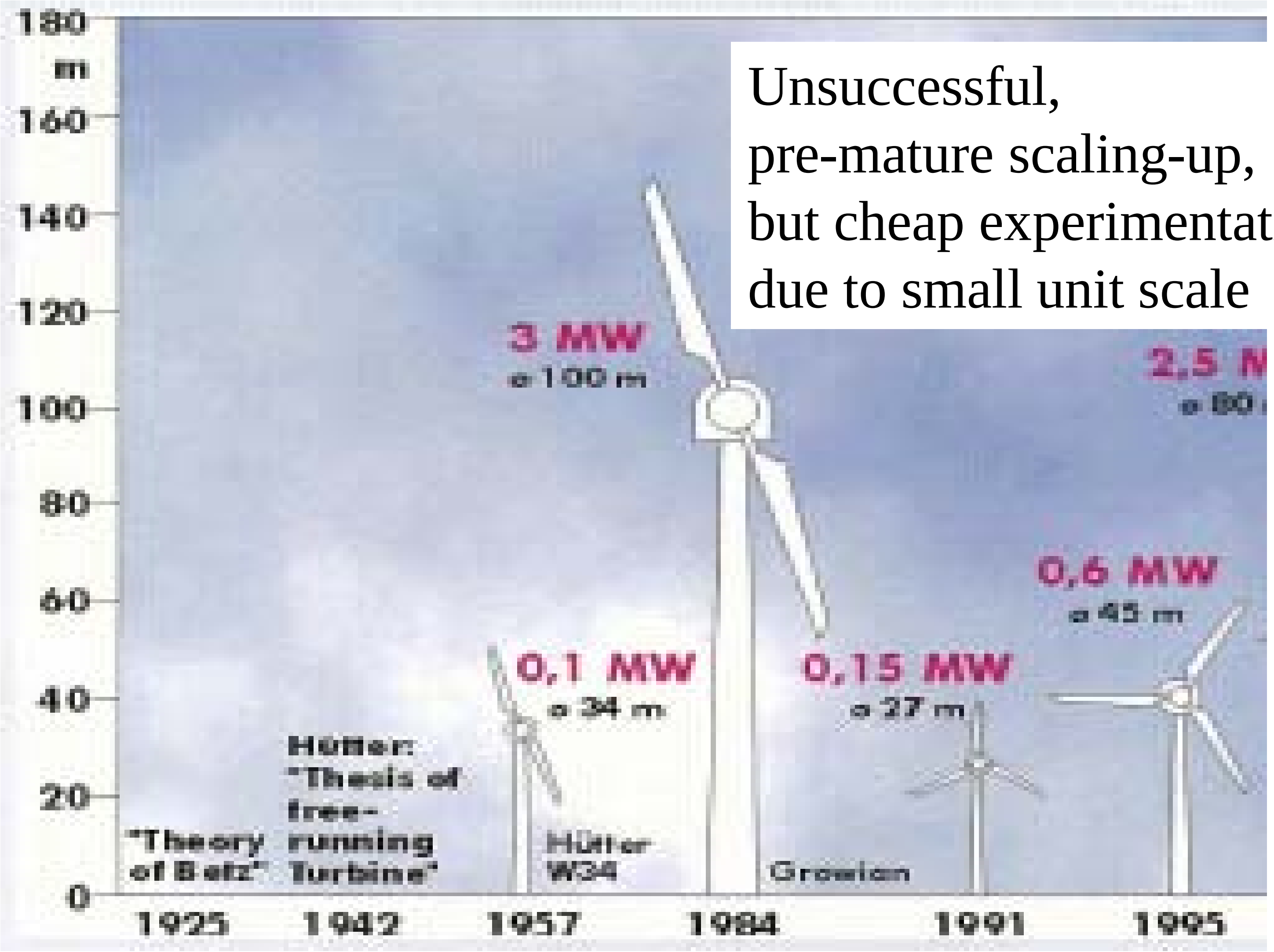
2.2. average



4: scale-up industry

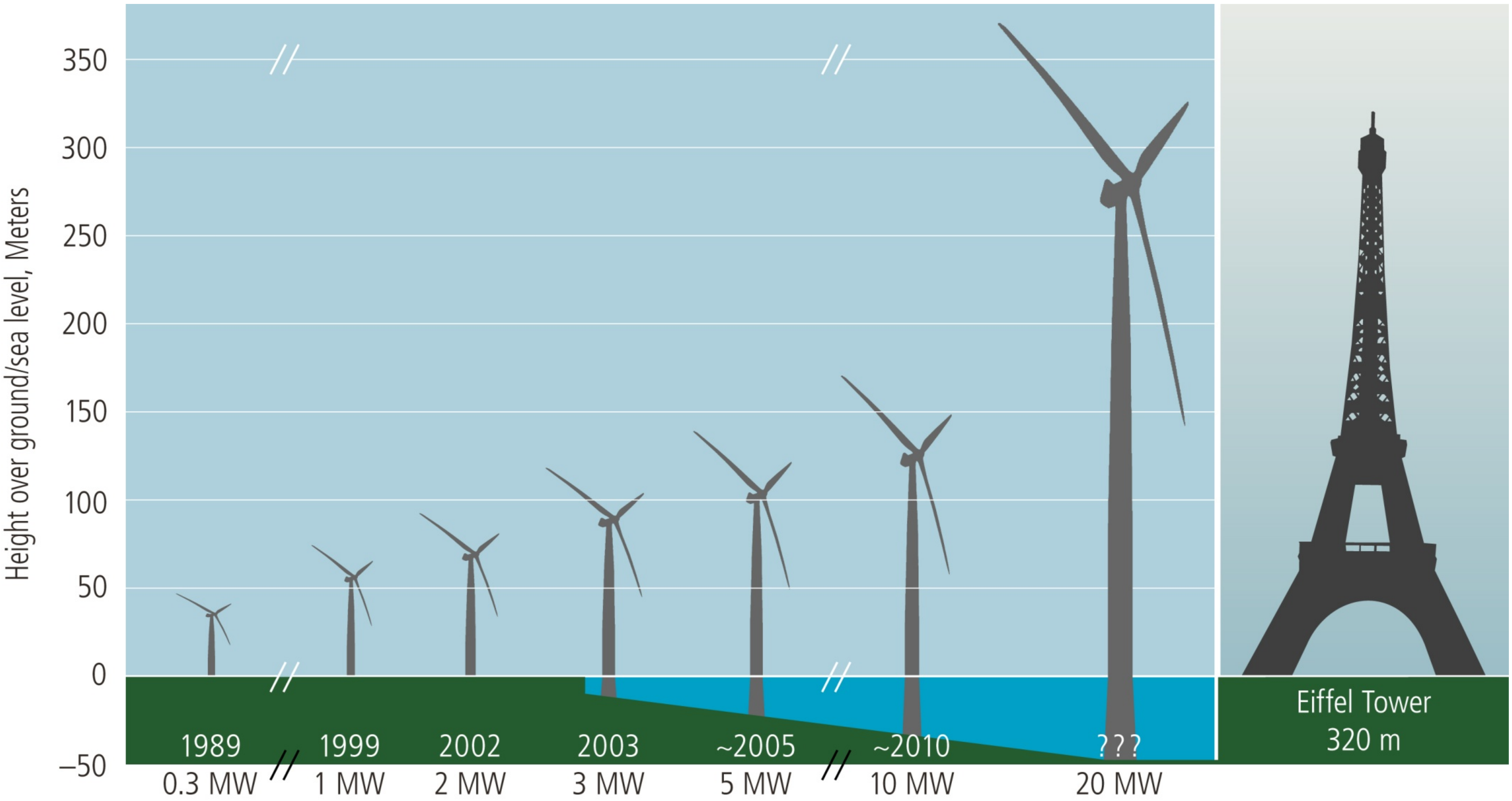
5: grow outside core markets (globalize)

Size of Wind Turbines 1



Unsuccessful,
pre-mature scaling-up,
but cheap experimentation
due to small unit scale

Size of Wind Turbines 2

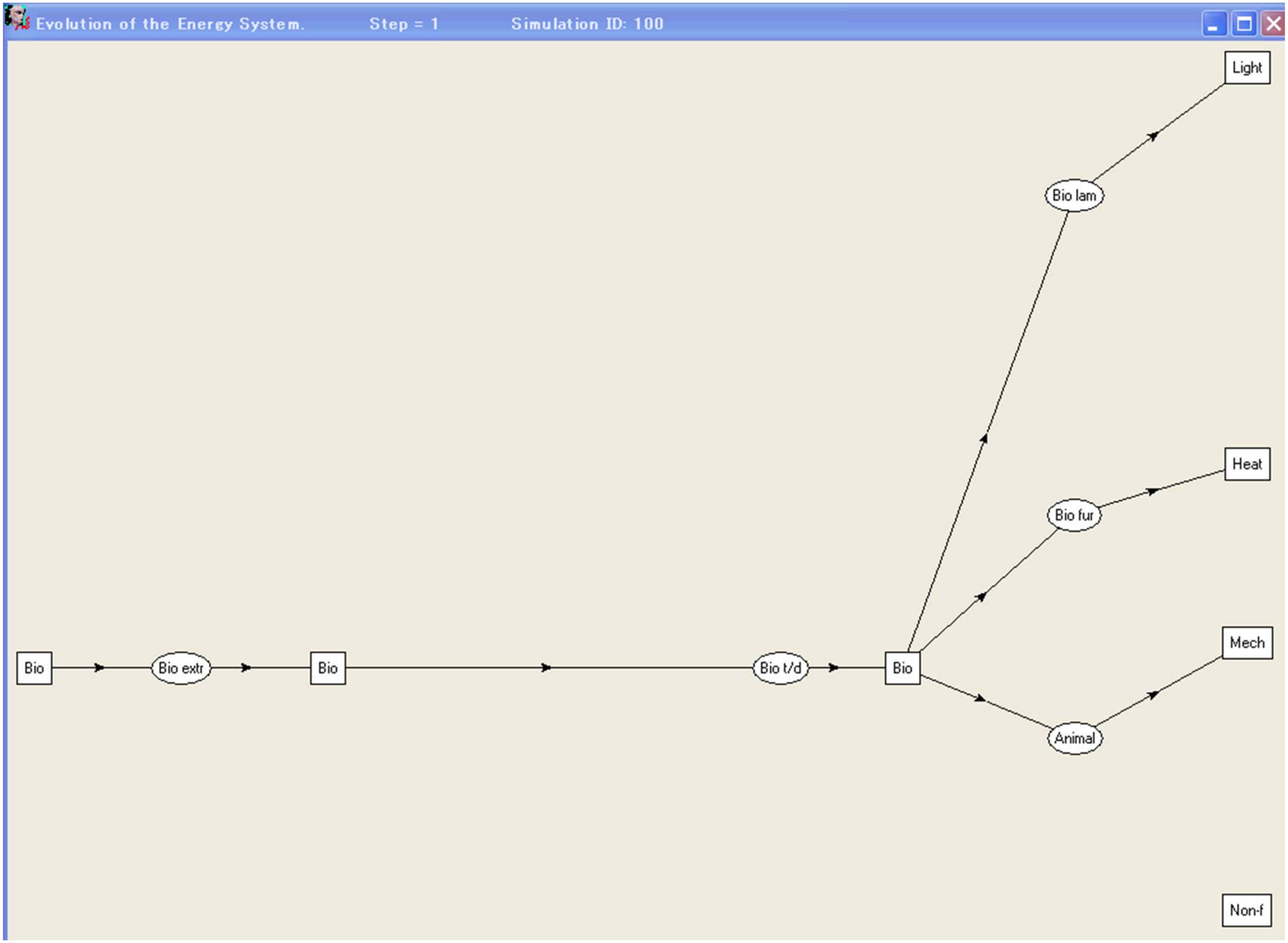


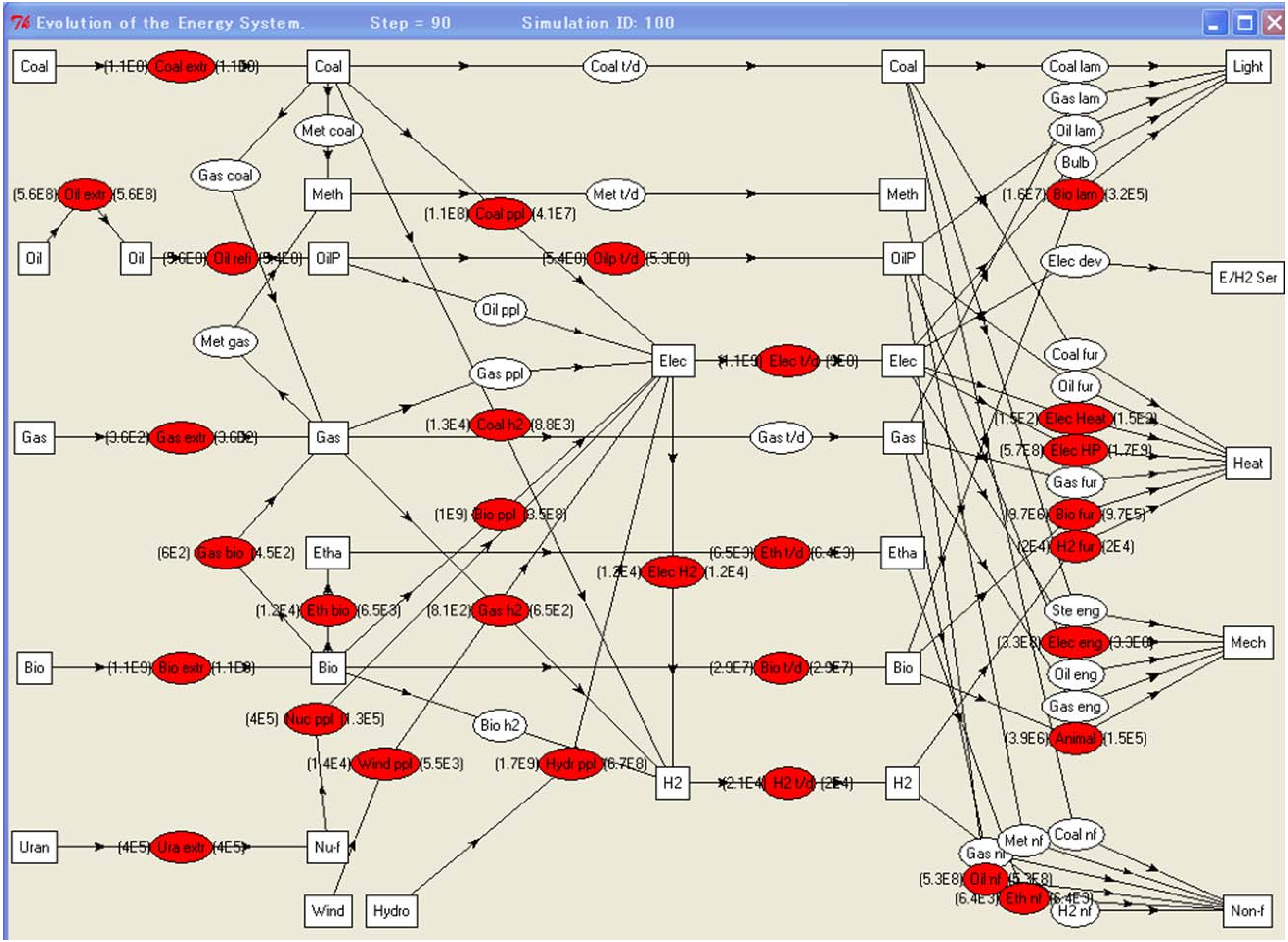
Appendix

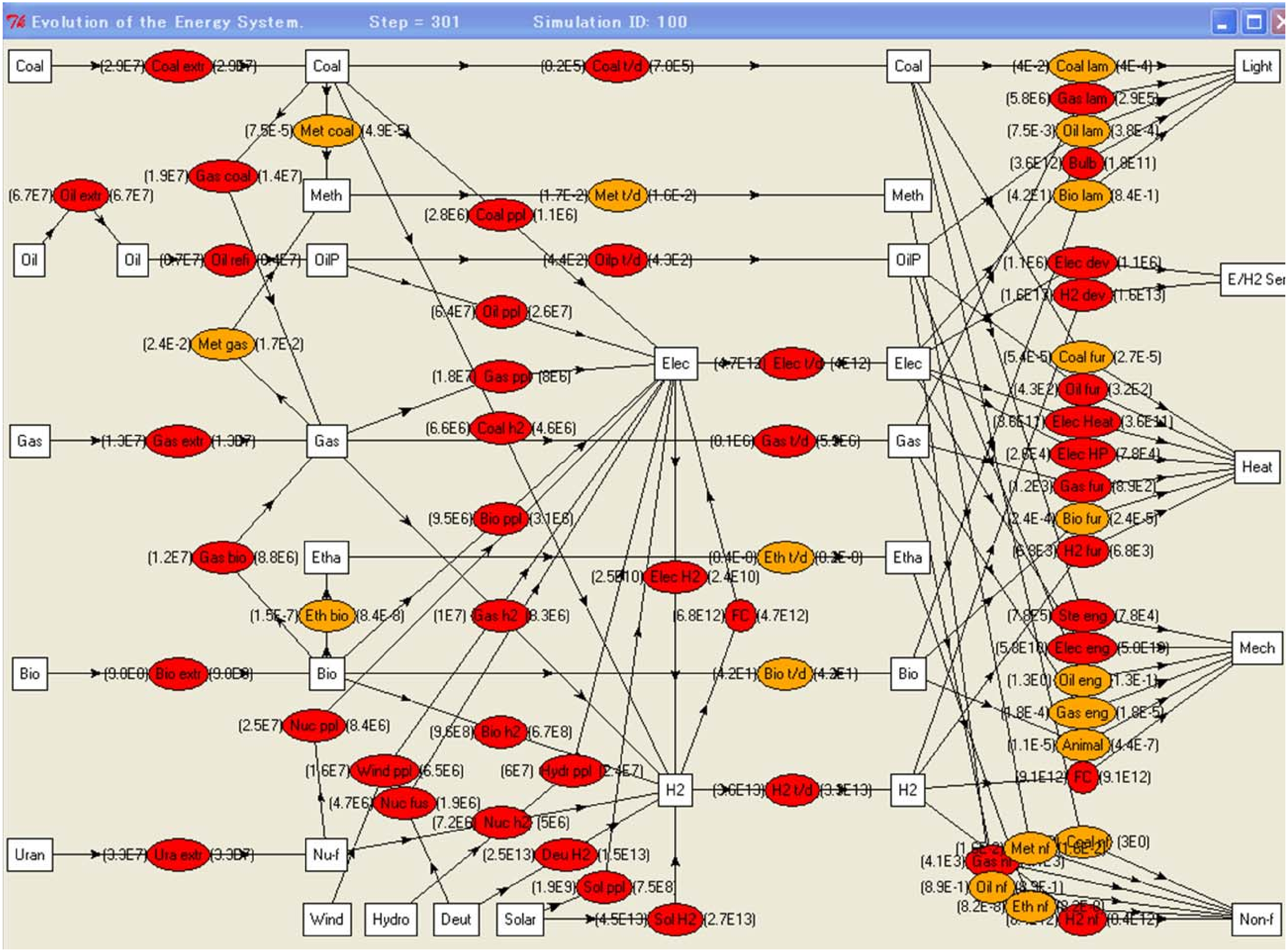
The Evolution of Technological Complexity

- Agent-based simulation model of the global energy system since 1800
- Random walk model of invention discovery and stochastic combination with other technologies into energy chains and systems
- Evolutionary selection environment
  - uncertain increasing returns
  - market share gains *f*(rel. advantage)
  - externalities (stochastic C-tax)
- $>10^2$ simulations (alternative histories and futures)
- Findings:
  -- trade-off between learning and diversity
  -- critical variable: innovation patience
  -- longevity of technologies and combinations needs explicit policy mechanism of "gales of creative destruction"

Ma T, Grubler A, Nakicenovic N, Arthur WB (2008).
Technologies as Agents of Change: A Simulation Model of the
Evolving Complexity of the Global Energy System. IIASA IR-08-021

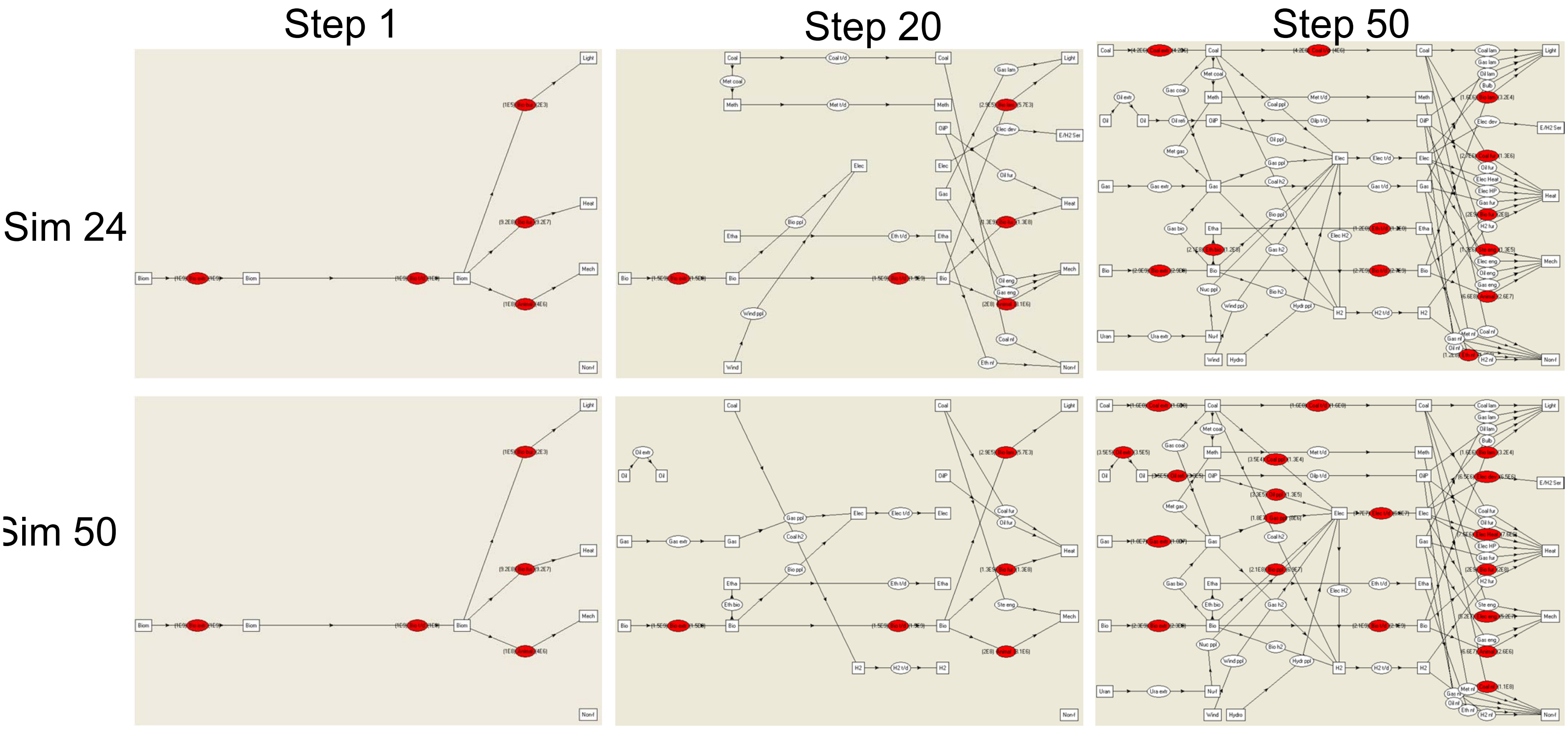

Evolution of the Energy System. Step = 1 Simulation ID: 100


Evolution of the Energy System. Step = 90 Simulation ID: 100
Coal
(1.1E0) Coal extr (1.1E0)
Coal
Coal t/d
Coal
Coal lam
Light
Gas lam
Met coal
Oil lam
Gas coal
Bulb
(5.6E8) Oil extr (5.6E8)
Meth
Met t/d
Meth
(1.6E7) Bio lam (3.2E5)
(1.1E8) Coal ppl (4.1E7)
Oil
Oil
(9.6E0) Oil refi (9.4E0)
OilP
(5.4E0) Oilp t/d (5.3E0)
OilP
Elec dev
E/H2 Ser
Oil ppl
Met gas
Elec
(1.1E9) Elec t/d (9E0)
Elec
Coal fur
Gas ppl
Oil fur
(1.5E2) Elec Heat (1.5E2)
Gas
(3.6E2) Gas extr (3.6E2)
Gas
(1.3E4) Coal h2 (8.8E3)
Gas t/d
Gas
(5.7E8) Elec HP (1.7E9)
Heat
Gas fur
(1E9) Bio ppl (3.5E8)
(9.7E6) Bio fur (9.7E5)
(6E2) Gas bio (4.5E2)
Etha
(6.5E3) Eth t/d (6.4E3)
Etha
(2E4) H2 fur (2E4)
(1.2E4) Elec H2 (1.2E4)
(1.2E4) Eth bio (6.5E3)
(8.1E2) Gas h2 (6.5E2)
Ste eng
(3.3E8) Elec eng (3.3E8)
Mech
Bio
(1.1E9) Bio extr (1.1E9)
Bio
(2.9E7) Bio t/d (2.9E7)
Bio
Oil eng
Gas eng
Bio h2
(4E5) Nuc ppl (1.3E5)
(3.9E6) Animal (1.5E5)
(1.4E4) Wind ppl (5.5E3)
(1.7E9) Hydr ppl (6.7E8)
H2
(2.1E4) H2 t/d (2E4)
H2
Uran
(4E5) Ura extr (4E5)
Nu-f
Gas nf
Met nf
Coal nf
(5.3E8) Oil nf (5.3E8)
(6.4E3) Eth nf (6.4E3)
H2 nf
Non-f
Wind
Hydro



Evolution of the Energy System.   Step = 301   Simulation ID: 100

Alternative Histories: Bifurcation and Lock-in



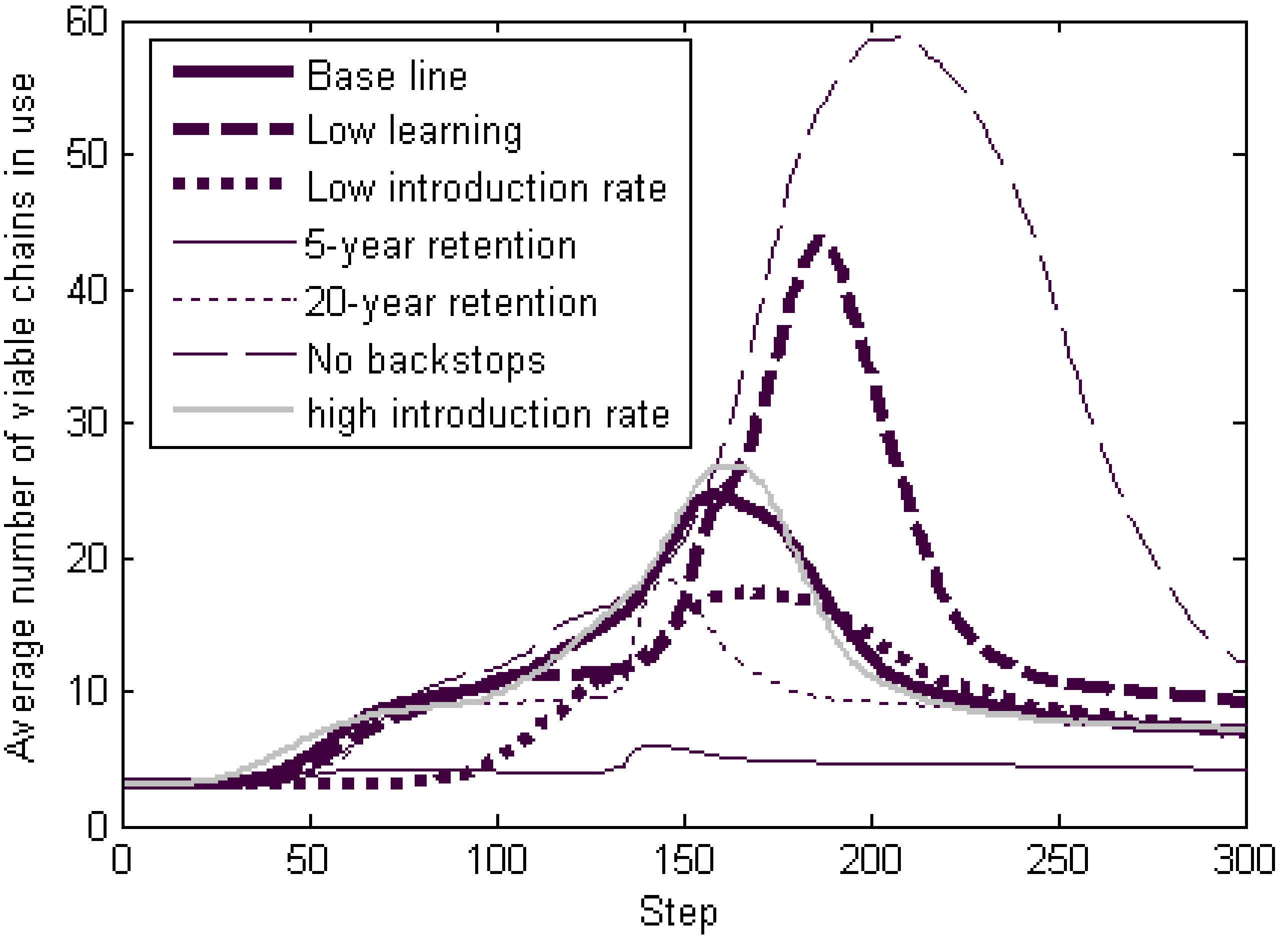
Same initial conditions, same model parametrization, but alternative developments:

Technology history arising from serendipity and chance?

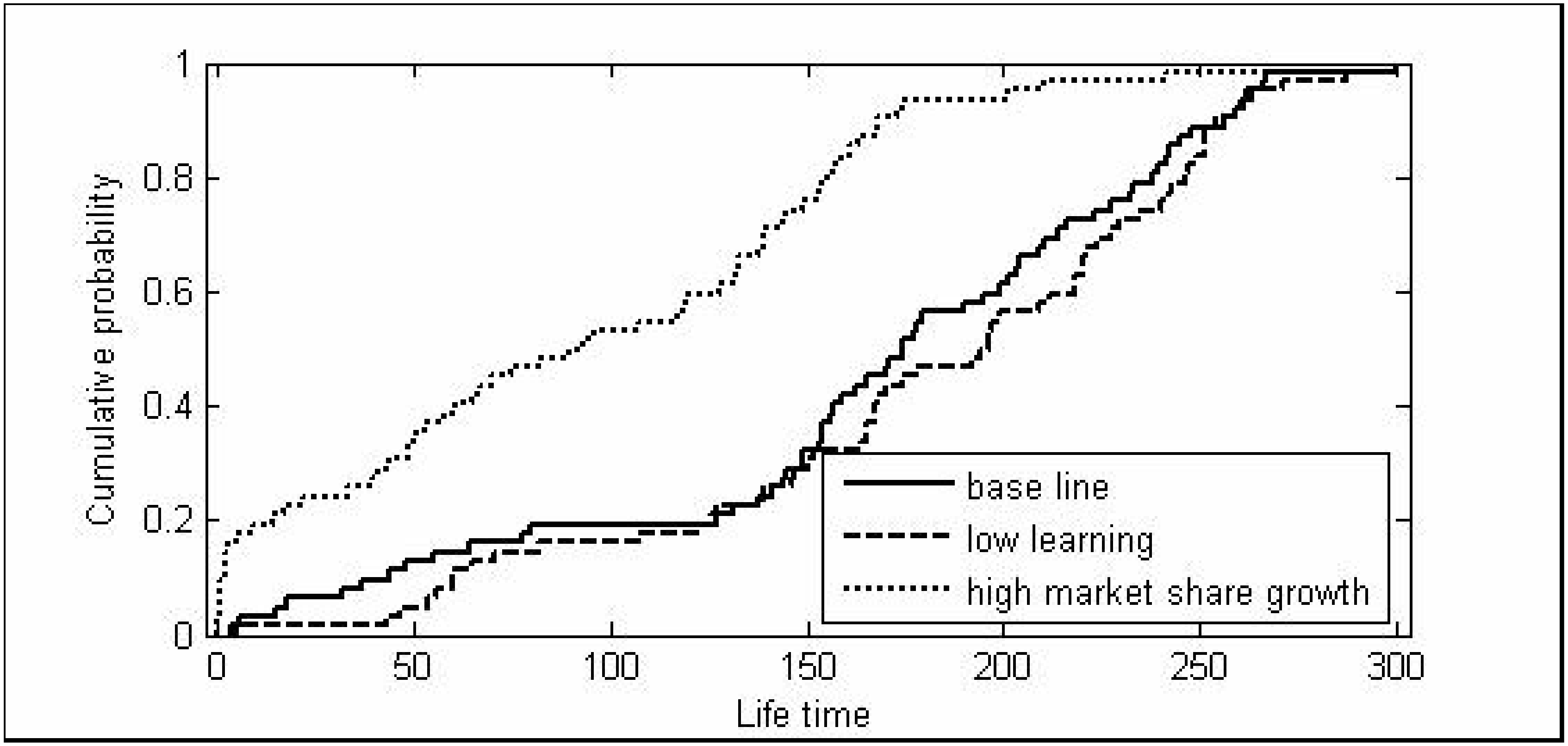
Evolution of Complexity

(avg. of 200 simulations each) and main determinants

- Learning rate and availability of backstops
- Innovation "impatience" (invention-innovation time lag)



Long Survival Time of Technologies:



Need to consider policy mechanisms for Schumpeterian "gales of creative destruction" under changing market environment, e.g. climate constraints