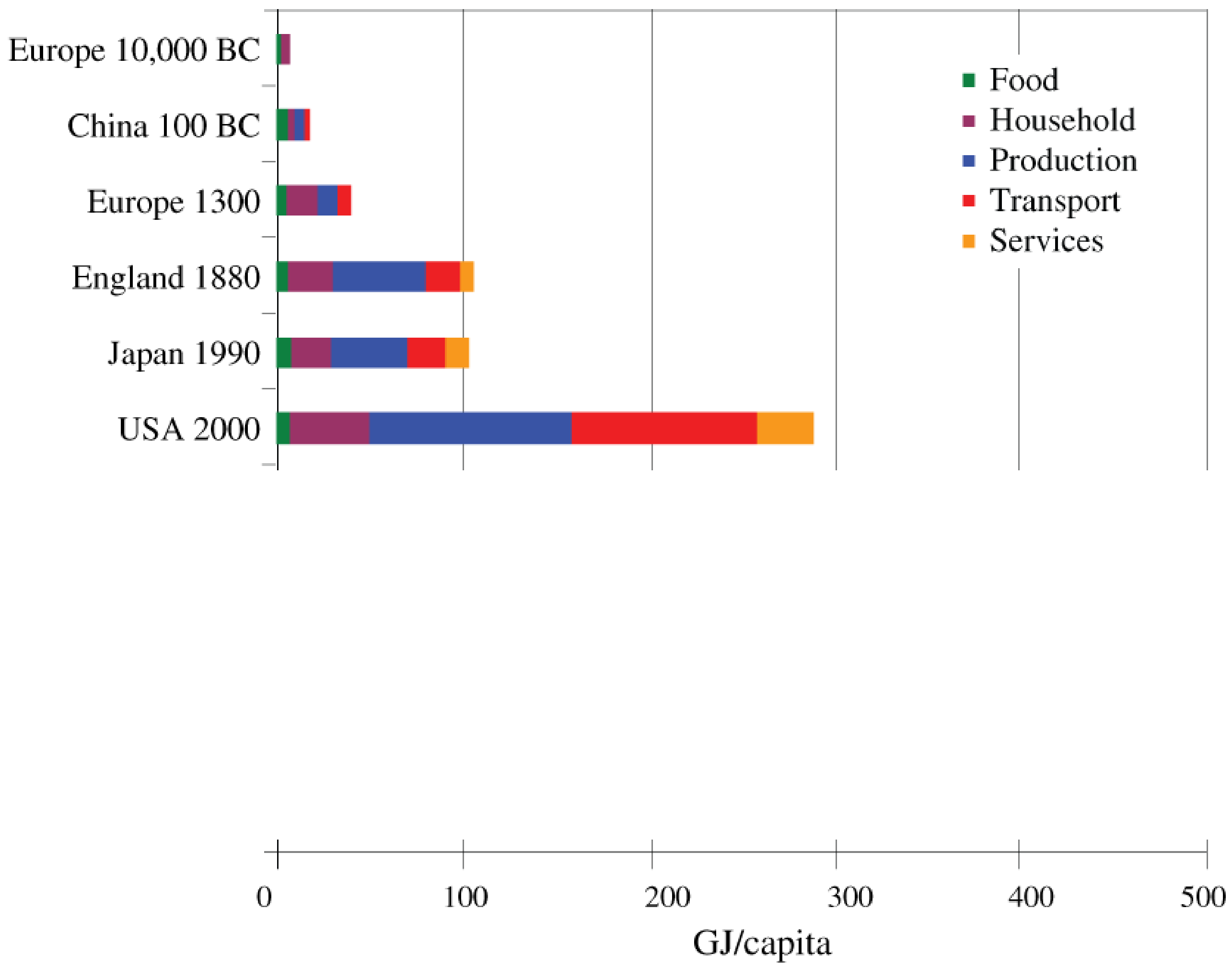
# Energy and Technology Transitions

arnulf.grubler@yale.edu

Hunter College, NYC, December 5, 2012

# Energy Transitions: Past

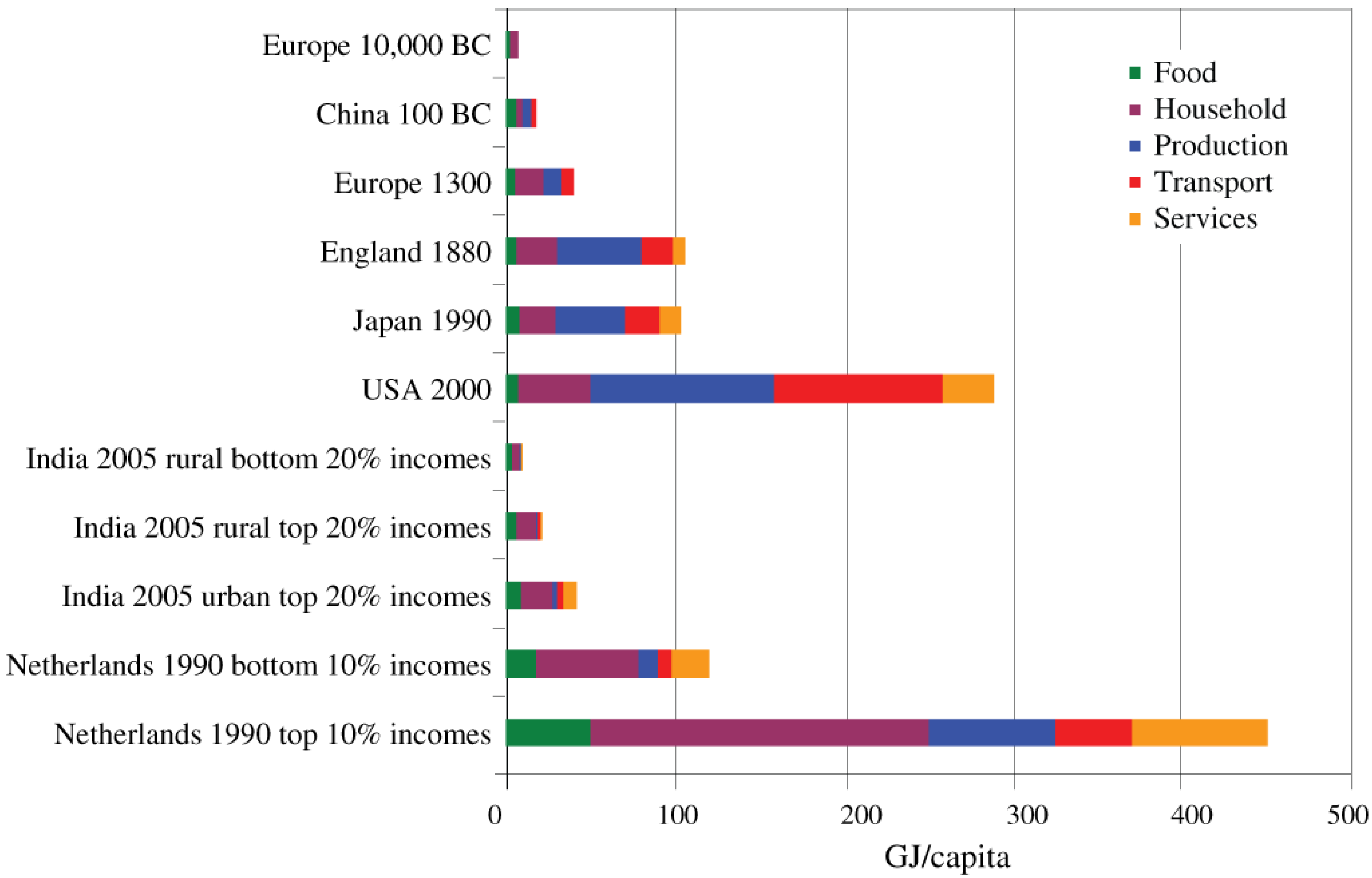



Source: adapted from V. Smil, 1994

# Energy Transitions: Drivers & Outcomes

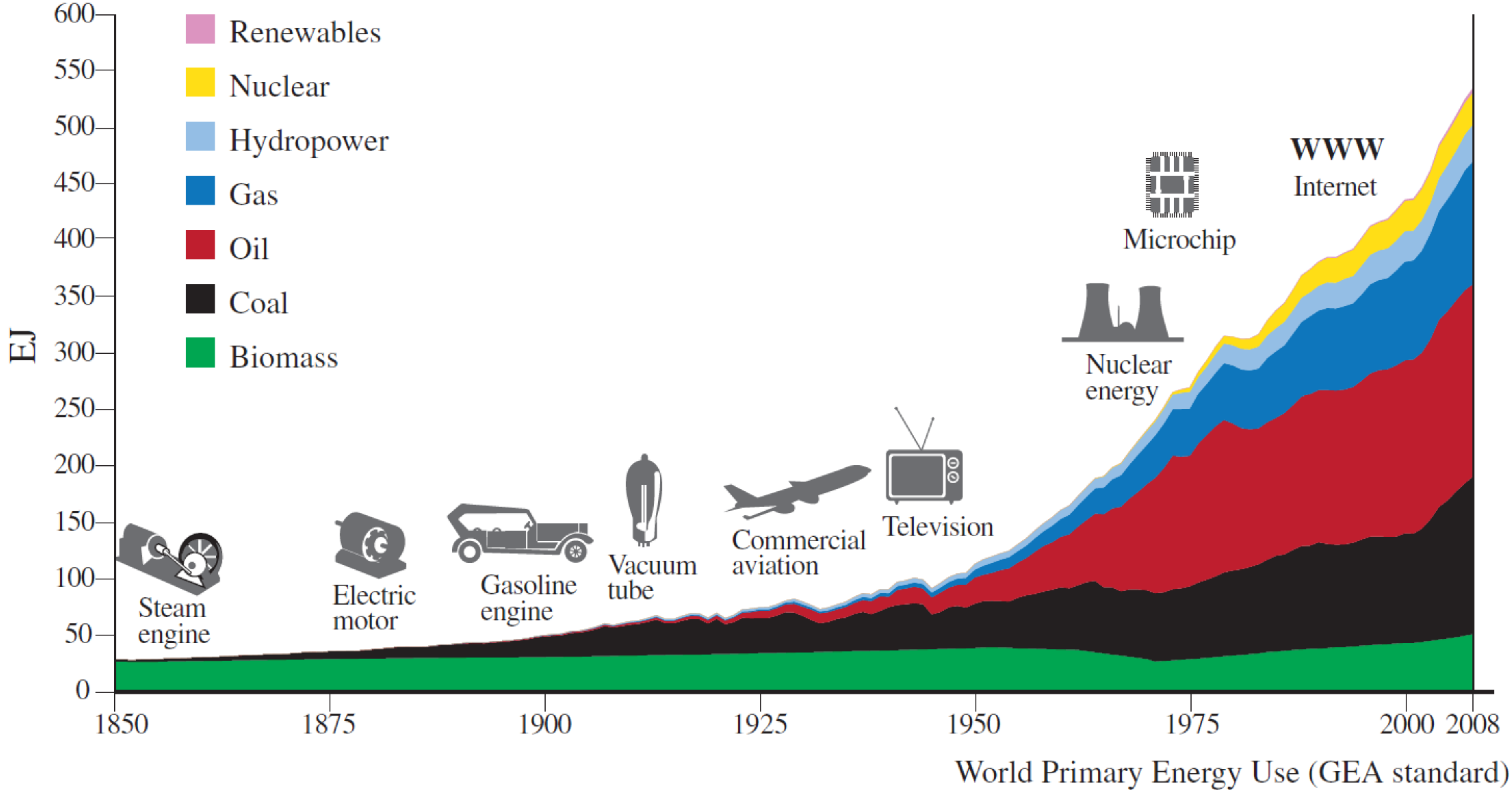
- Overcome constraints:
  - availability
  - density
  - lack of diversity
- Technological change enables to:
  - provide novel energy services
  - improved efficiency
  - expanded & diversified supply
  - lessened trad. environmental impacts (indoor air pollution, "decarbonization")
- Demand & economic growth, and <u>new</u> environmental impacts (climate)

# Energy Transitions: Present (unfinished business)




Source: Global Energy Assessment (GEA) KM1, 2012

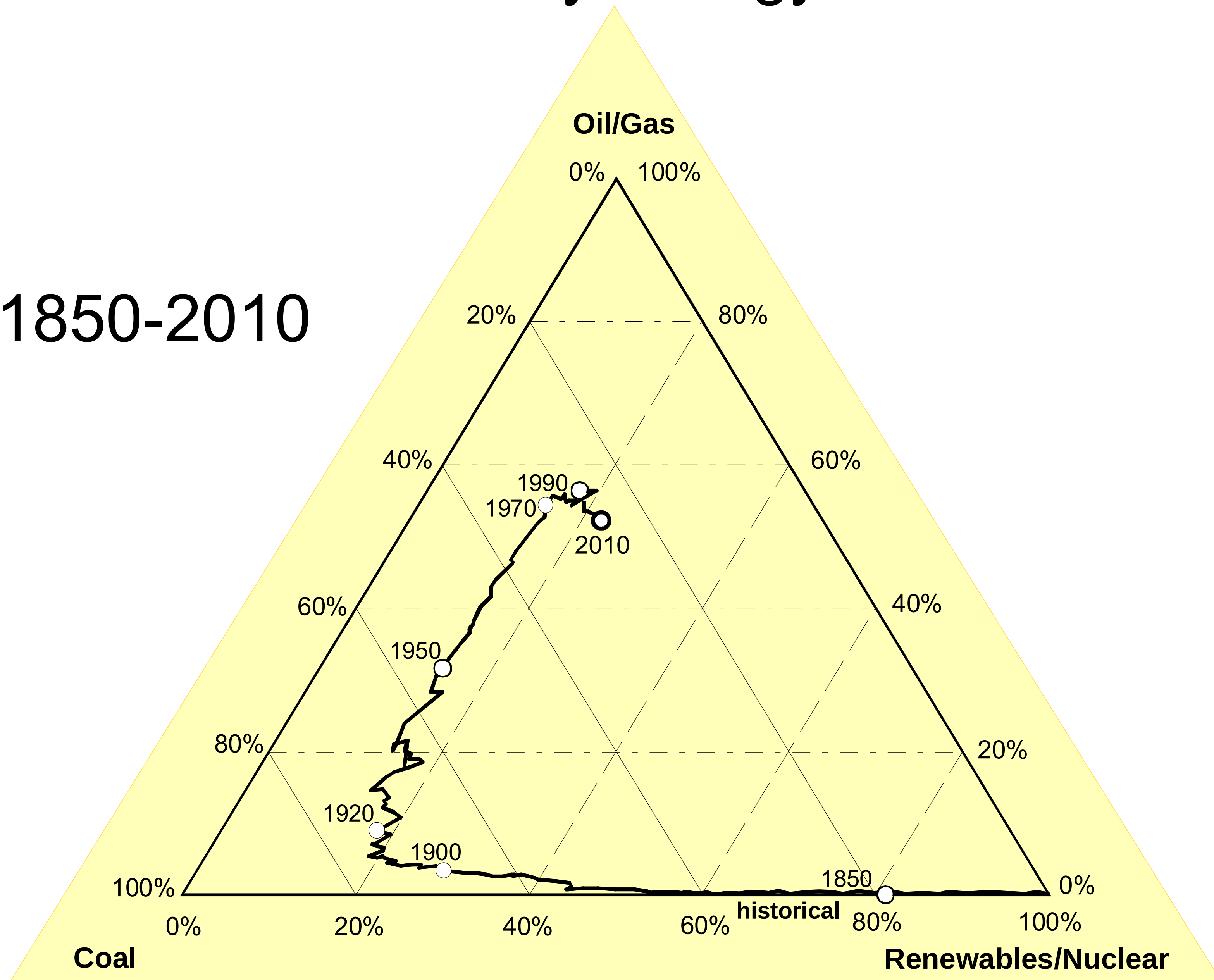
# Energy Transitions - The Traditional View: Measuring Primary Energy Inputs



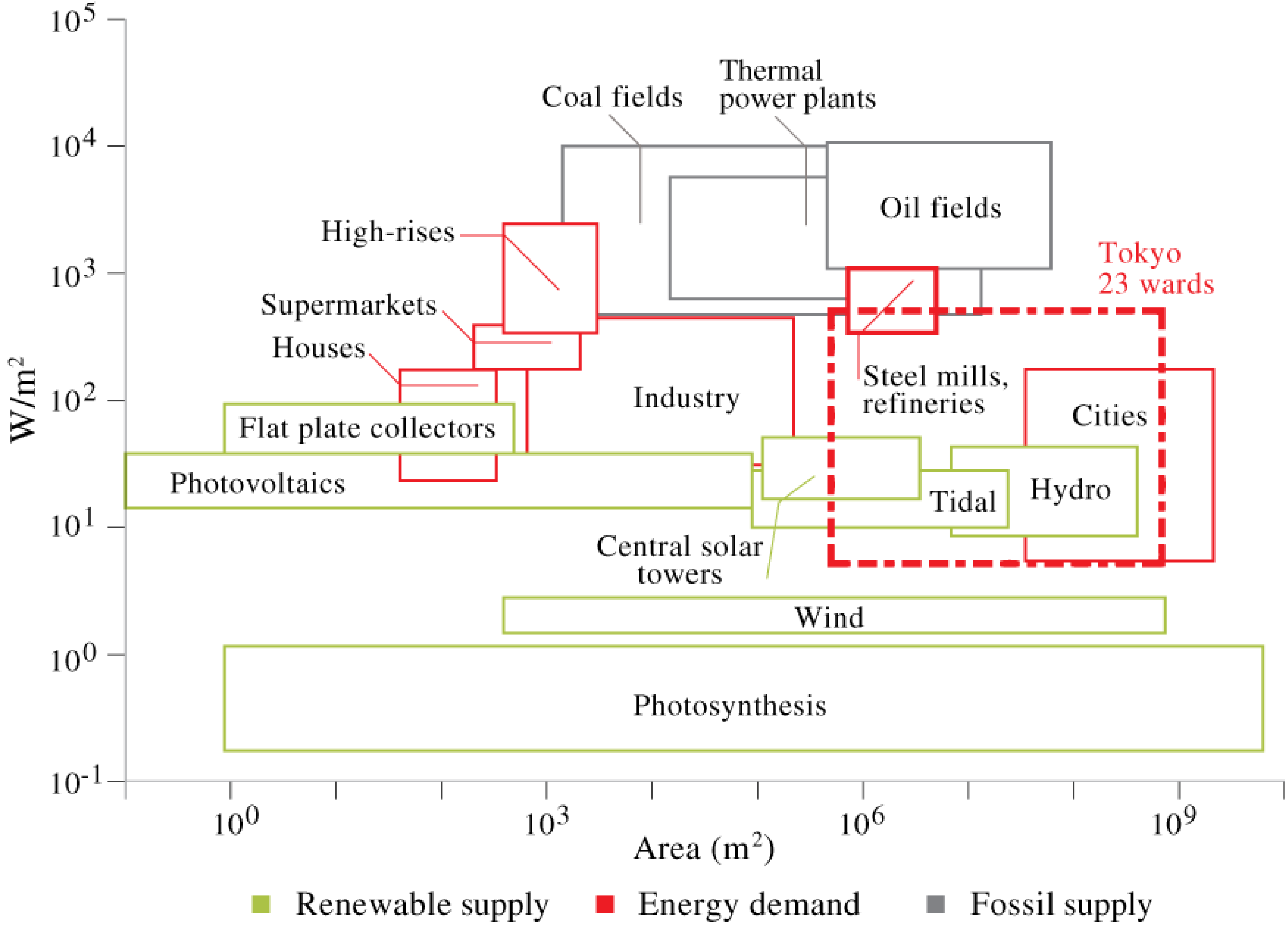

Source: Global Energy Assessment (GEA) KM1, 2012

# World Primary Energy Shares

## 1850-2010



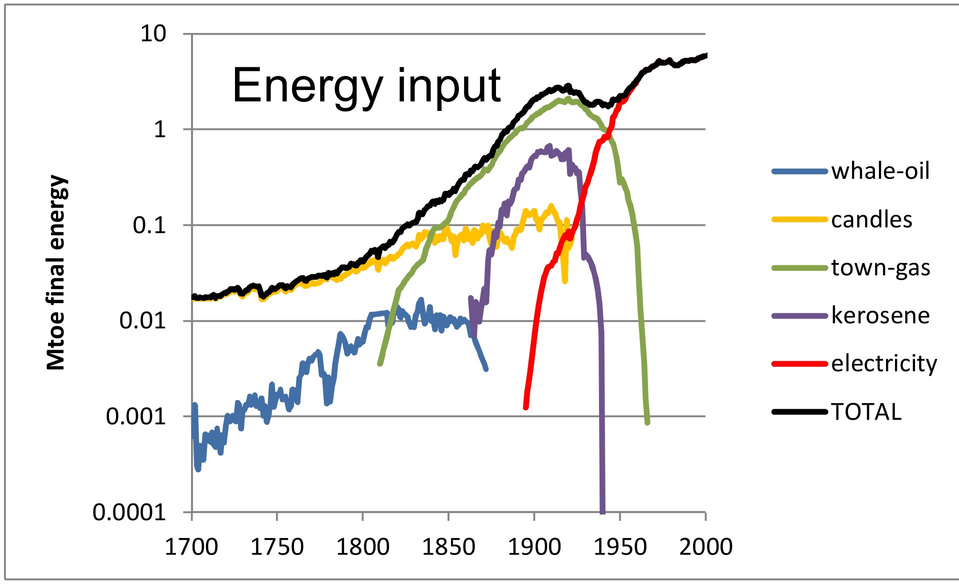
# Power Densities of Energy Supply & Demand

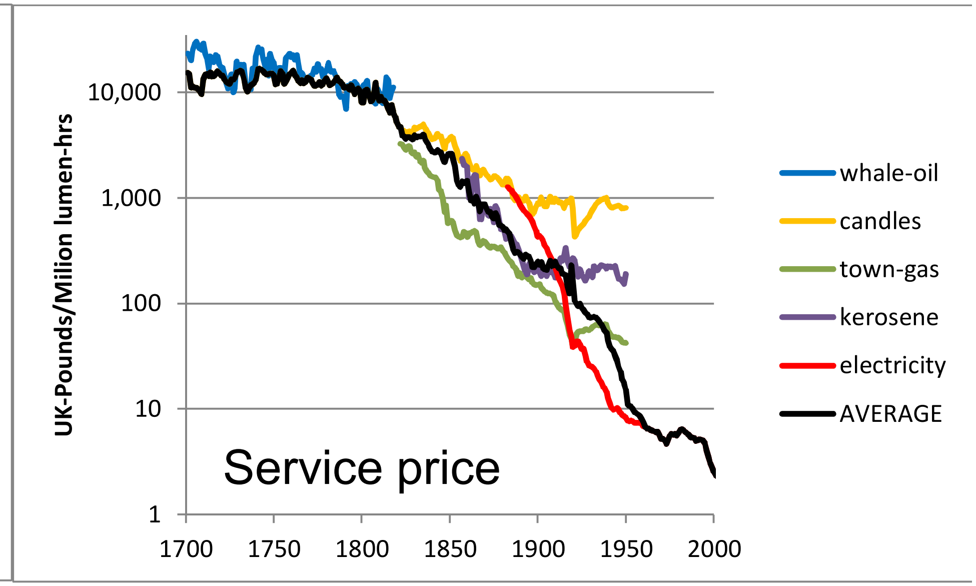


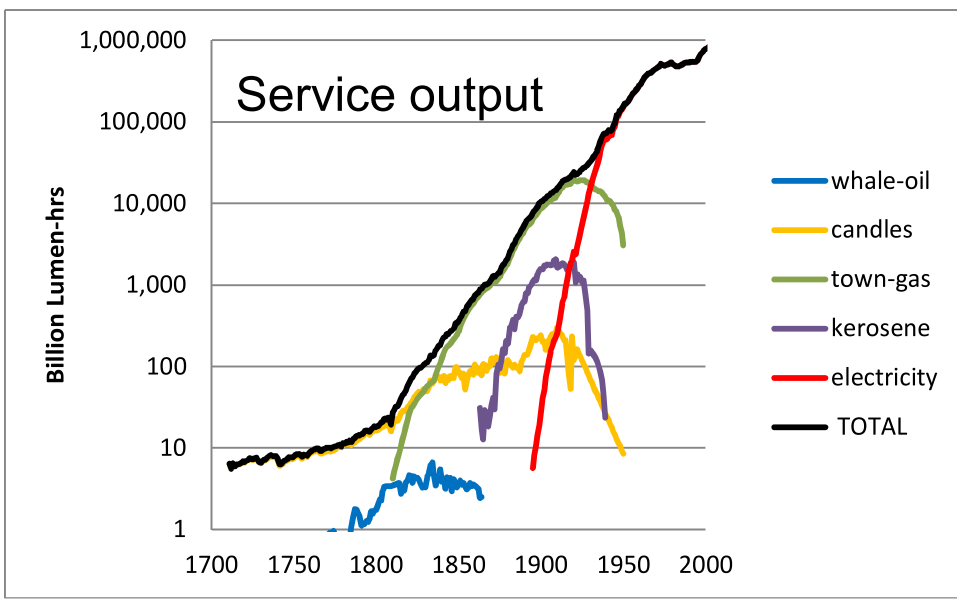

Source: Global Energy Assessment (GEA) KM1, 2012

# The End-use/Service Output Perspective of Transitions.
# Example: UK Lighting

Data: R. Fouquet, 2008




Factors of Increase & drivers

supply

energy input: x 300

efficiency

service output: x 150,000

learning, scale economies

service price: ÷ 6,500

# Lessons from Energy Transition Research

- Lesson 1: Energy-end use key
- Lesson 2: Multiple, interacting drivers
- Lesson 3: Technology, efficiency, costs, and welfare gains interact
- Lesson 4: Powerful patterns (scaling, rates of change,…)
- Lesson 5: Impact of policies mixed

# Lesson 1: Energy End-use Key

- End-use: dominant form of energy conversion and dominant mobilizer of energy investments (and jobs!)
- Least efficient part of energy system (highest improvement potential)
- Largely “market” driven but with important externalities and barriers (information gaps, myopia, principal-agent problems, social & environmental externalities)
- Decentralized and “granular” decisions & technologies
- Stepchild of “silver bullet”, “top-down” (supply-side biased) policies

# Capacity of US Energy Conversion Technologies

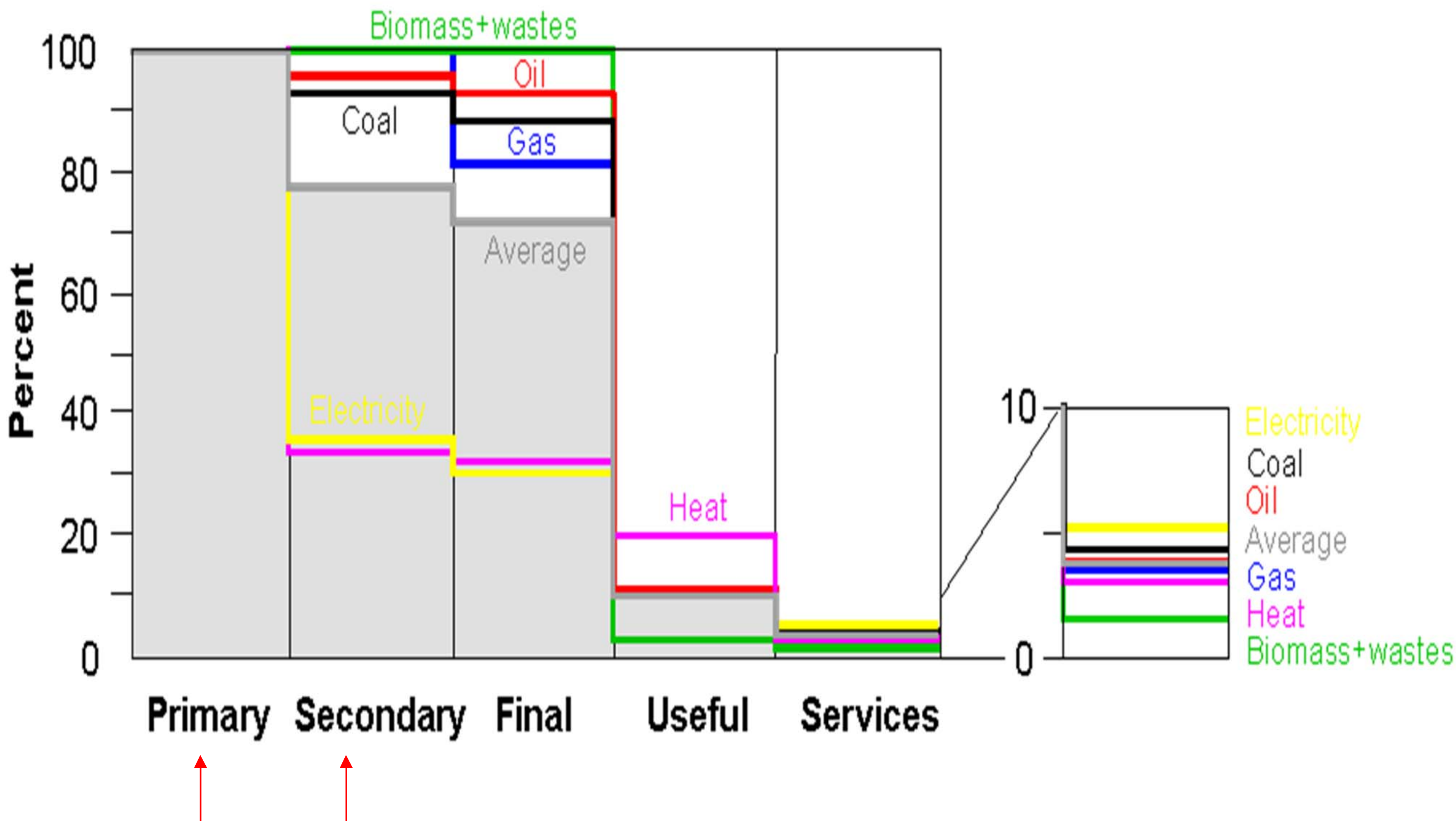
| GW (rounded) | | 1850 | 1900 | 1950 | 2000 |
|---|---|---|---|---|---|
| stationary | thermal (furnaces/boilers) | *300* | *900* | *1900* | *2700* |
| end-use | mechanical (prime movers) | 1 | 10 | 70 | 300 |
| | electrical (drives, appliances) | *0* | *20* | *200* | *2200* |
| mobile | animals/ships/trains/aircraft | 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

# Exergy Efficiency of OECD Energy Systems

(as % of primary exergy by conversion stage)




Traditional focus of energy transition research

Source: GEA KM1, 2012

# Investment into Energy Technology by Category and Life-cycle Stage. World in 2005 (billion US$)

| | **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 |

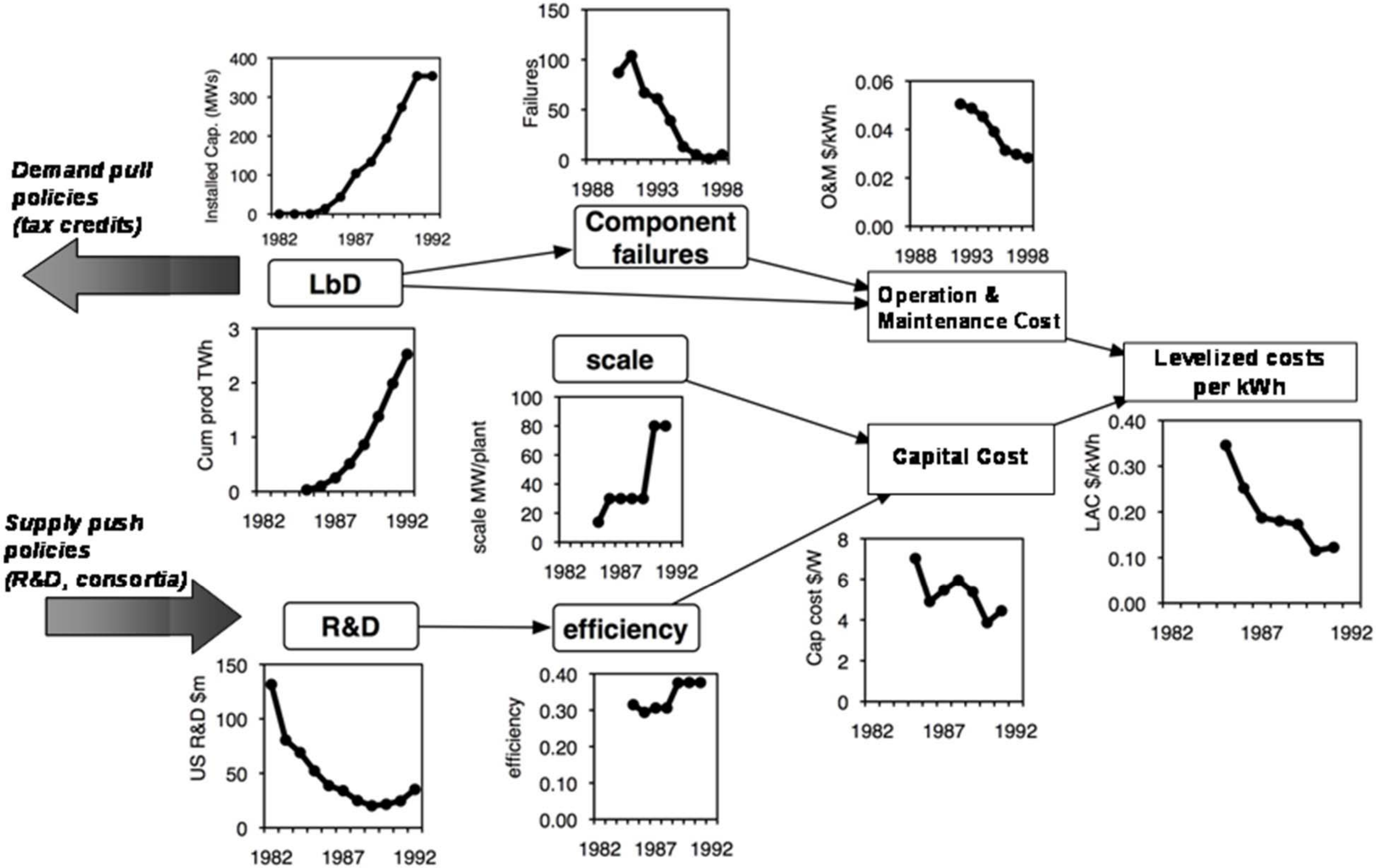
* hydrogen, fuel cells, other power & storage technologies, basic energy research

Source: GEA KM24, 2012

# Lessons 2&3: Interacting Drivers and Linkages
income↔costs↔market size↔innovation↔TFP growth

- Micro-level:
  - demand pull AND supply push
  - extended development cycles, vulnerable to policy intermittency and knowledge obsolescence
- Macro-level:
  major interactions between economy, technology, and energy services (but poorly documented)

# US Solar Thermal Virtuous Development Cycle

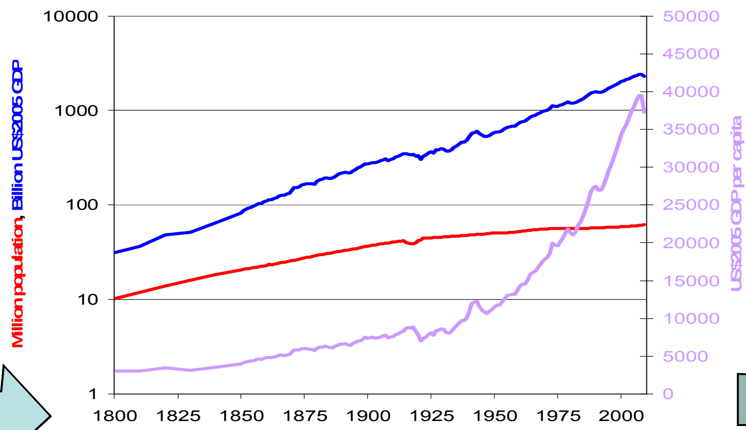



Source: GEA KM24, 2012 based on G. Nemet, 2011

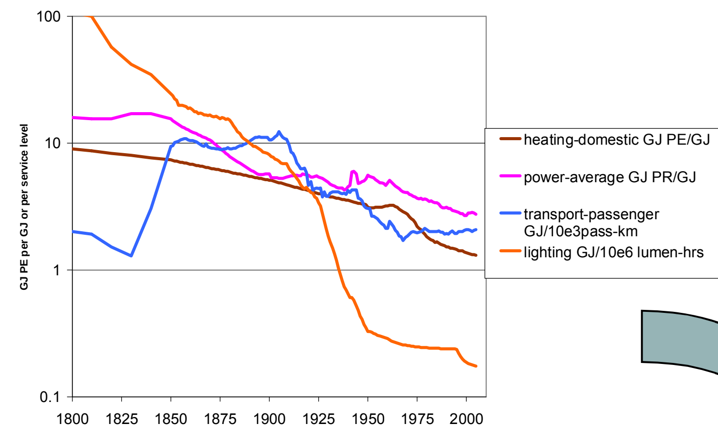
# UK Energy History

## A story of interlinked positive feedback loops

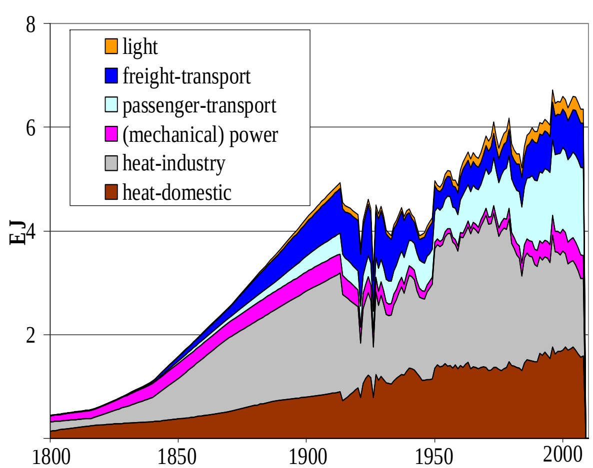
### Population and Income



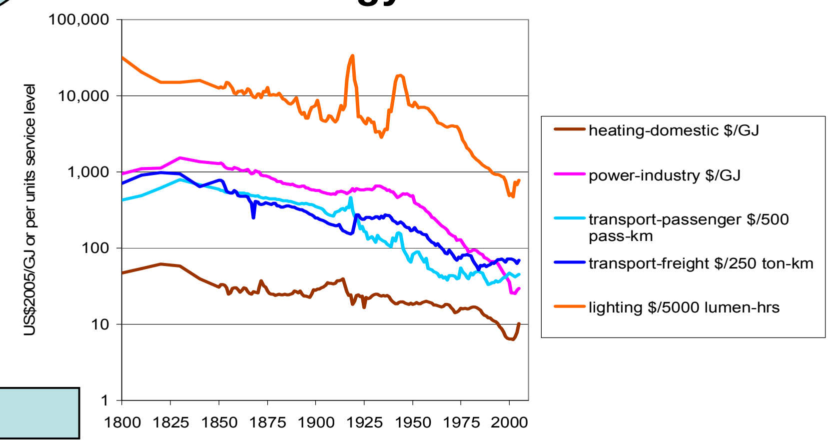

### Innovation and LbD: efficiency of end use




### Energy service demands




### +Market growth and LbD: cost of energy services



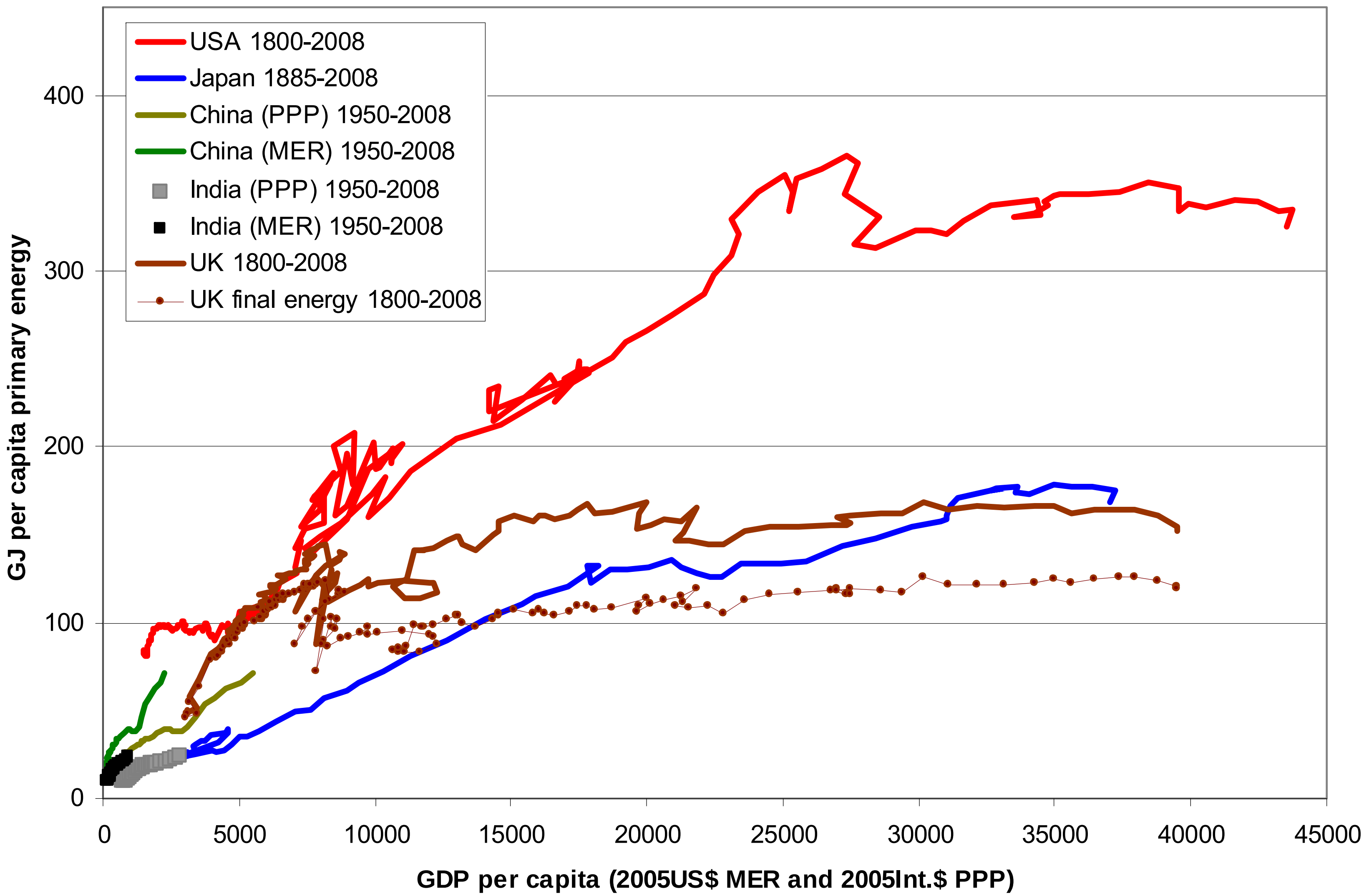

LbD=Learning by Doing

Source: GEA KM1, 2012

# Lesson 4: Powerful Patterns

- Path dependencies (multiple authors) but discontinuities remain enigma
- Scaling patterns and dynamics (C. Wilson)
- Lessons from systems and diffusion theories (IIASA)
- New concept: “granularity” (GEA KM24) smaller unit scale of technology=smaller investment risk, more learning/experimening possibilities

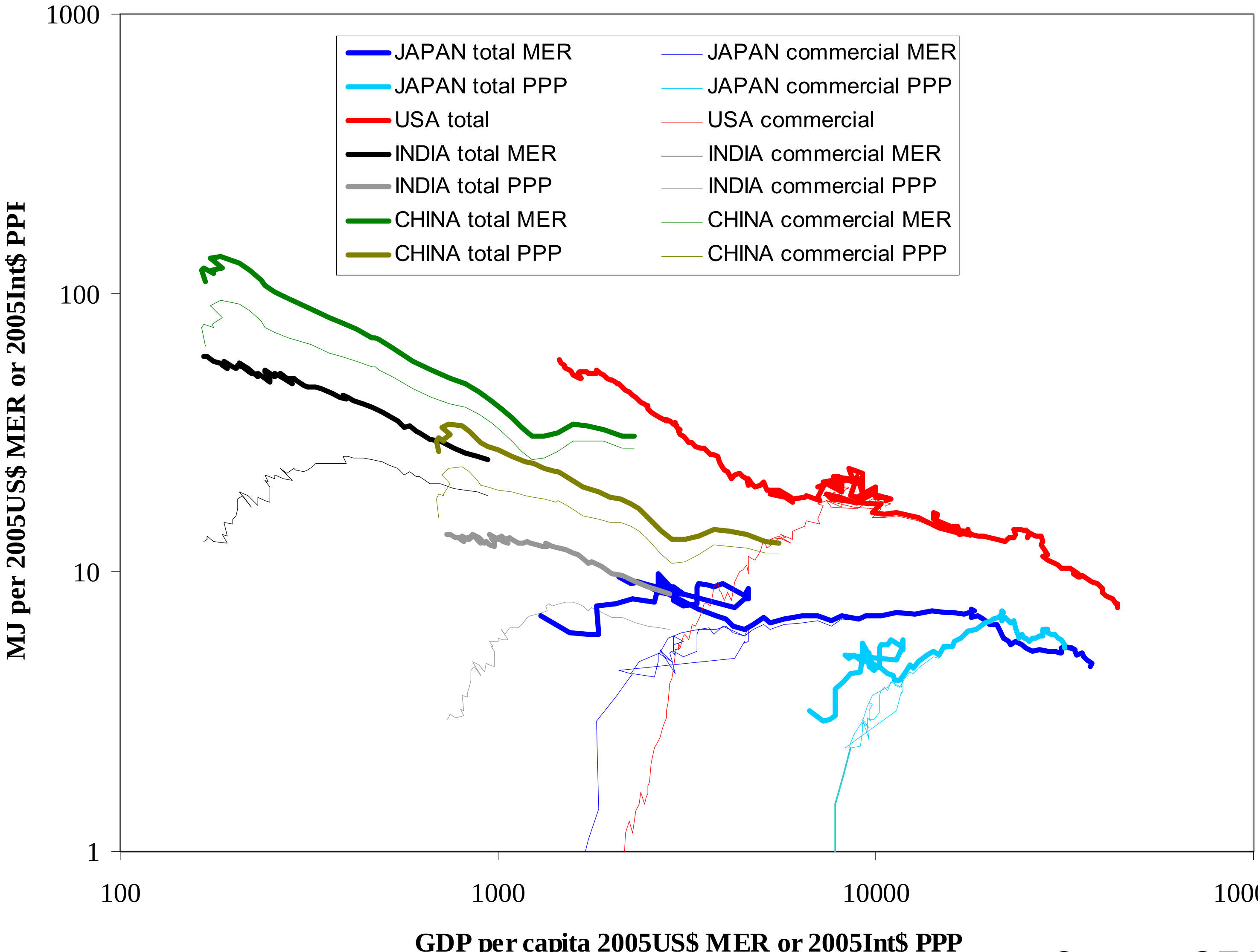
# Path Dependency & Historical Discontinuities in Energy Use vs Wealth




Source: GEA KM1, 2012

# Path Dependent Energy Intensities

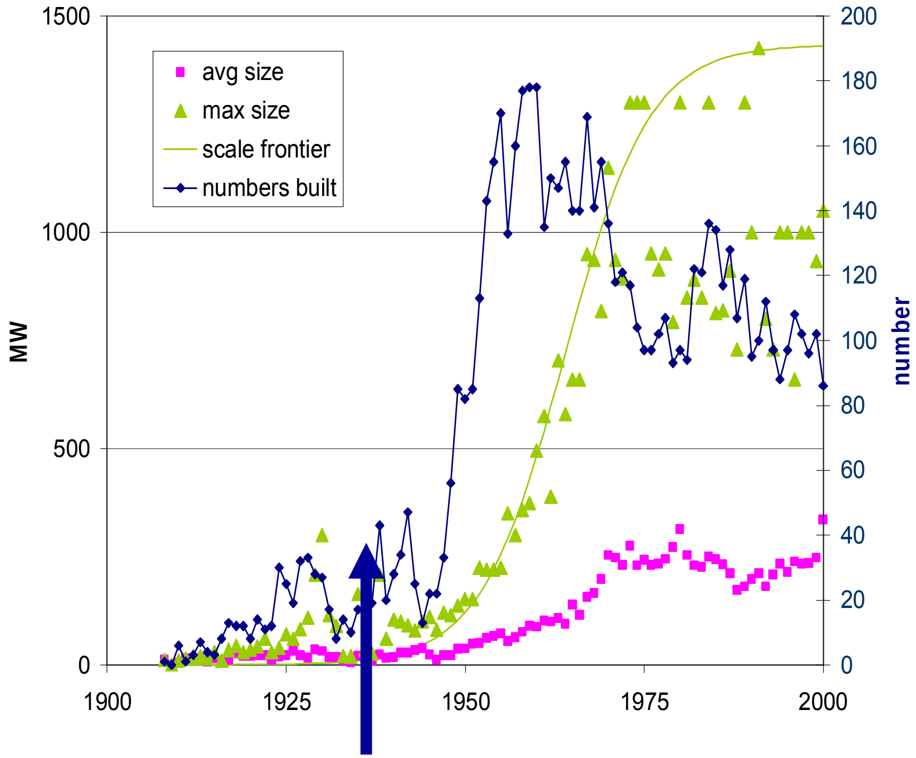
total & commercial (only), per $ MER and $ PPP




Source: GEA KM1, 2012

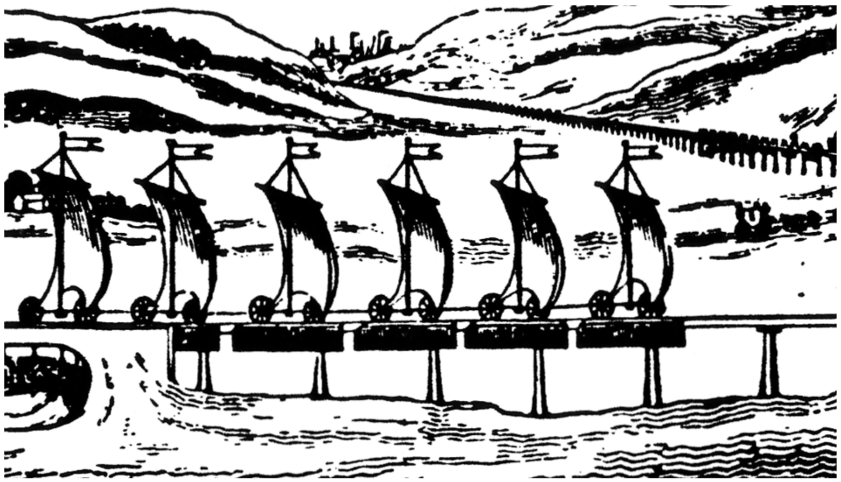
# 5 Phases in Scaling-up of a Technology:

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




**1: build many (small) units**

**1. Experimentation**
**Decades long process of experimentation and learning with small-scale technologies diverse designs and multitude of actors, many failures**



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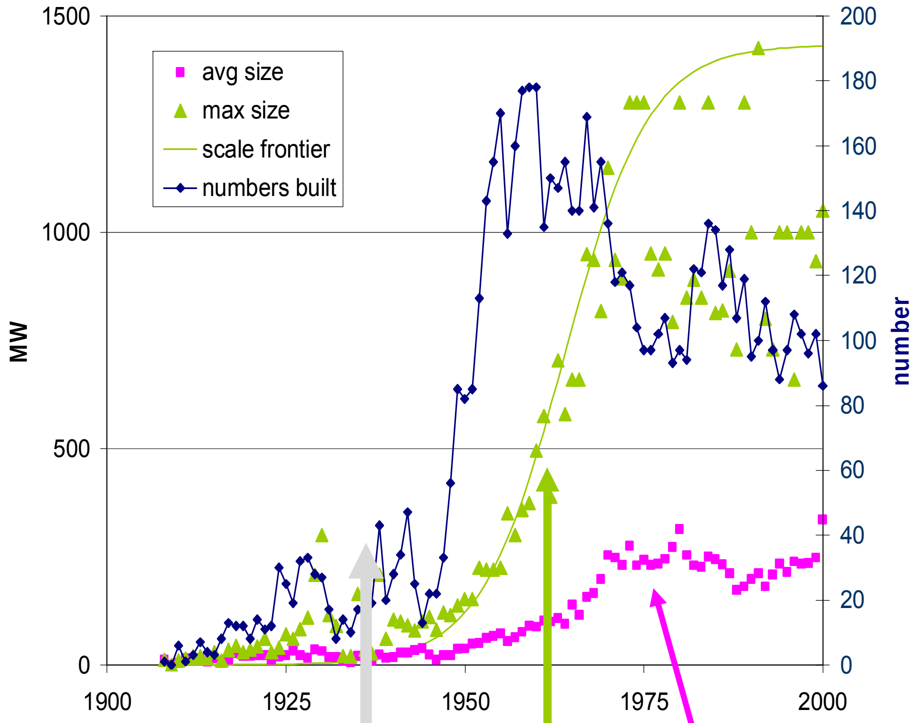


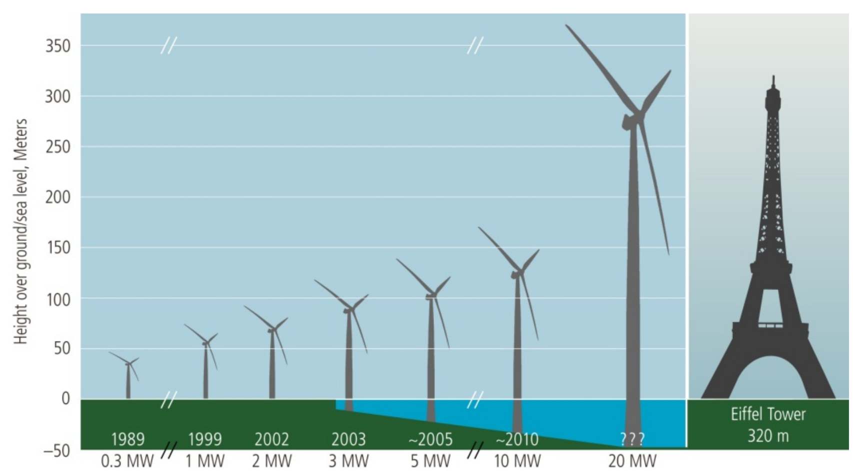

1: build many (small) units

2: scale-up units:

2.1. at frontier

2.2. average

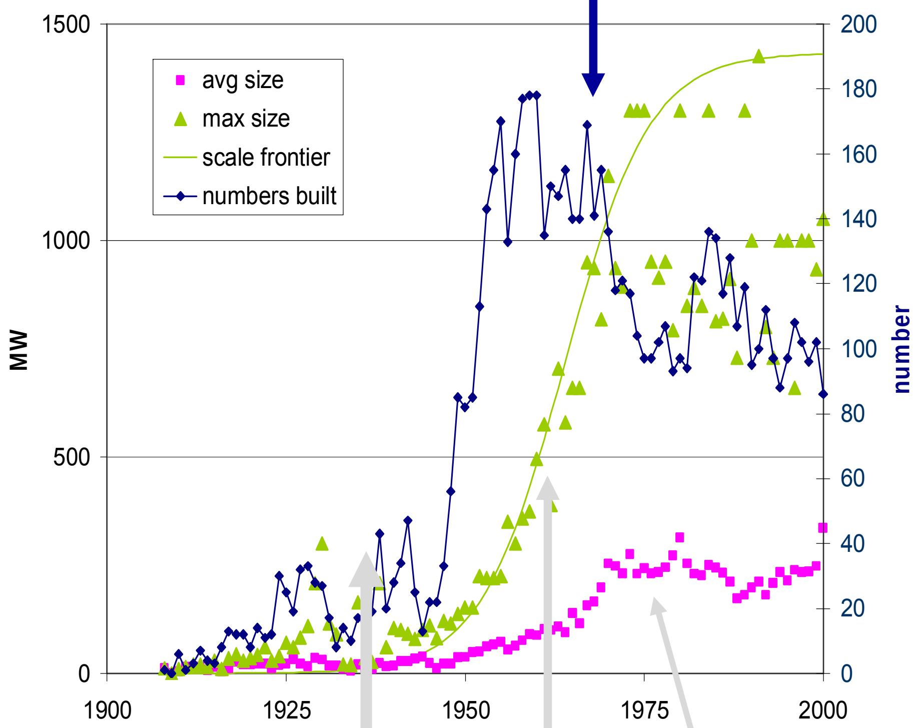
**2. Scaling at unit scale level emerging standardized design allows scaling and economies of scale effects, risks of pre-mature standardization or "too big too early"**



# 5 Phases in Scaling-up of a Technology:

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

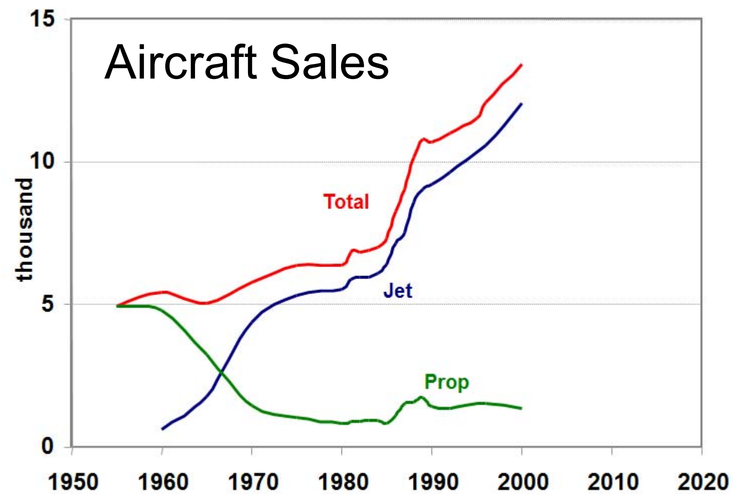
**3: build many (large) units**




**1: build many (small) units**

**2: scale-up units:**
**2.1. at frontier**
**2.2. average**

**3. Market growth in core**
**After reaching unit scale-frontier growth by selling many large units**



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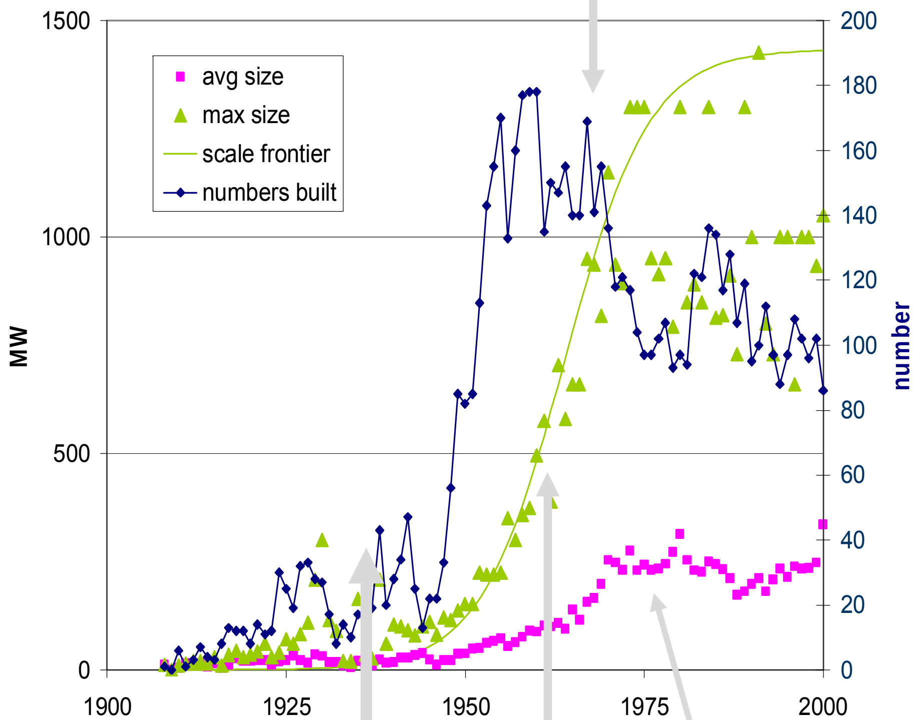


1: build many (small) units

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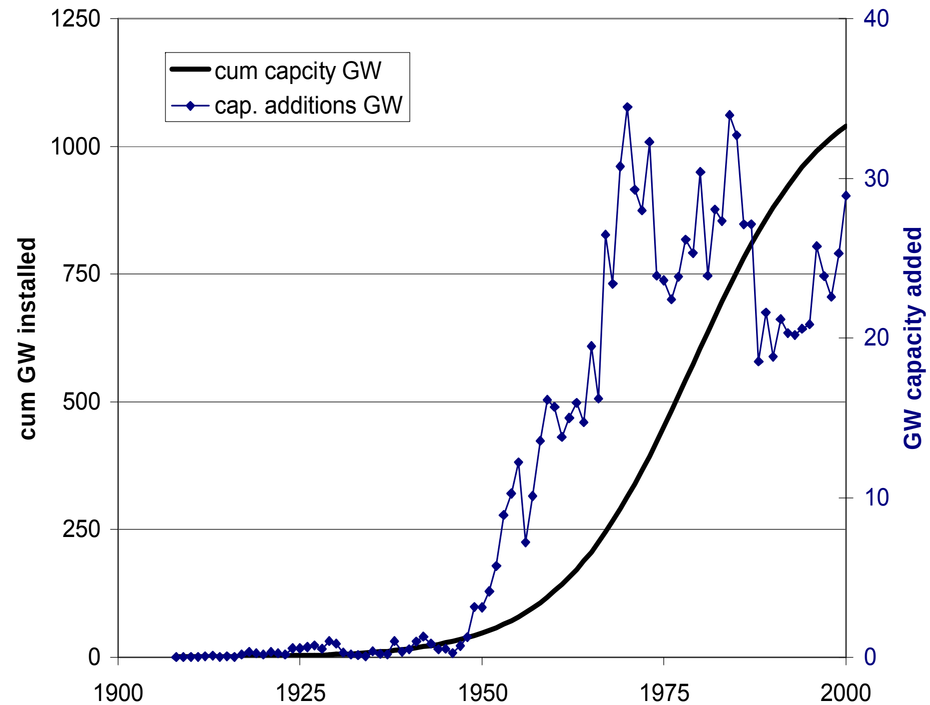
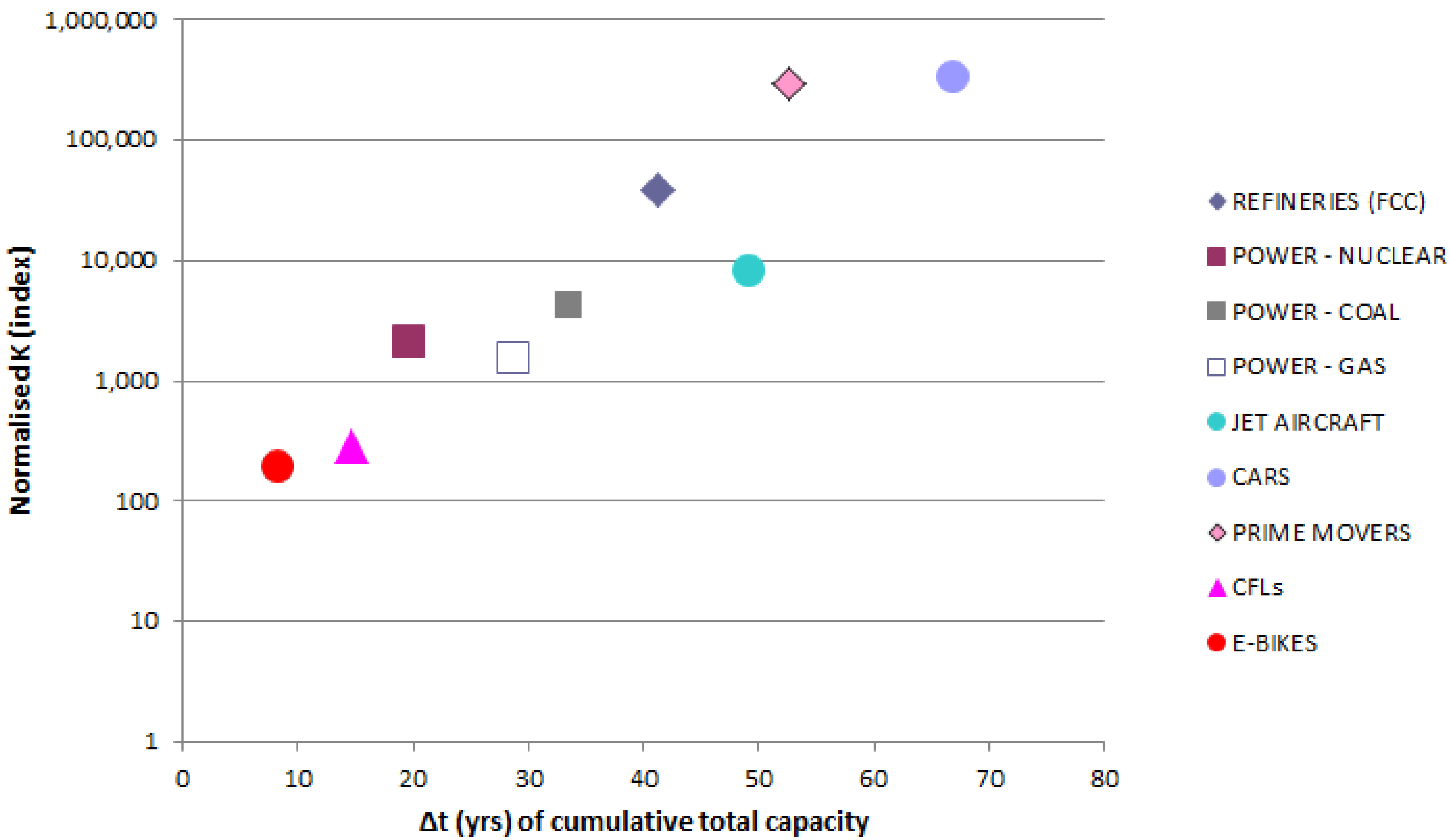
2.2. average




**4: scale-up industry**

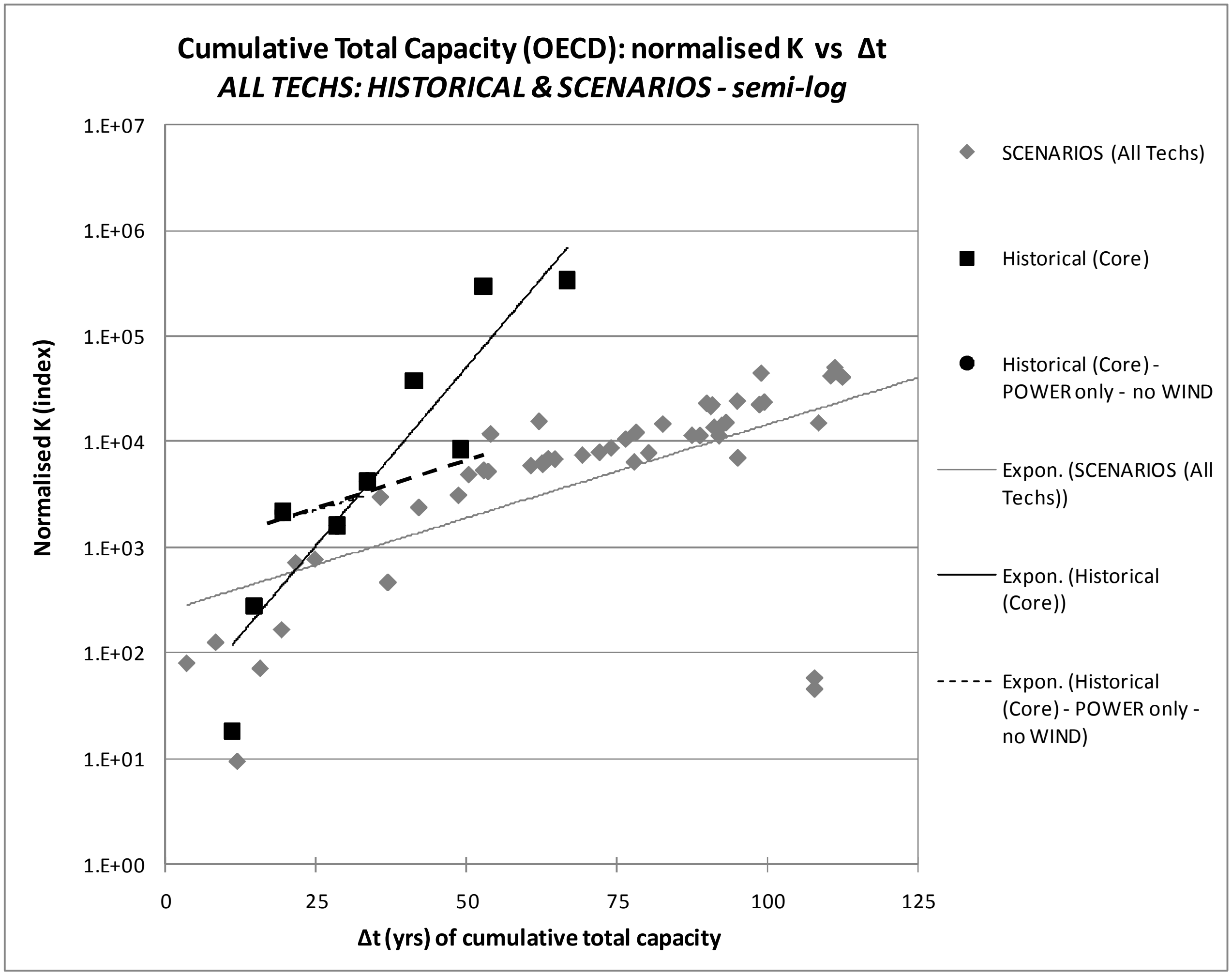
**5: grow outside core markets (globalize)**

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




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

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




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

# Learning rates and cumulative experience (# of units produced/sold): Importance of "Granularity"

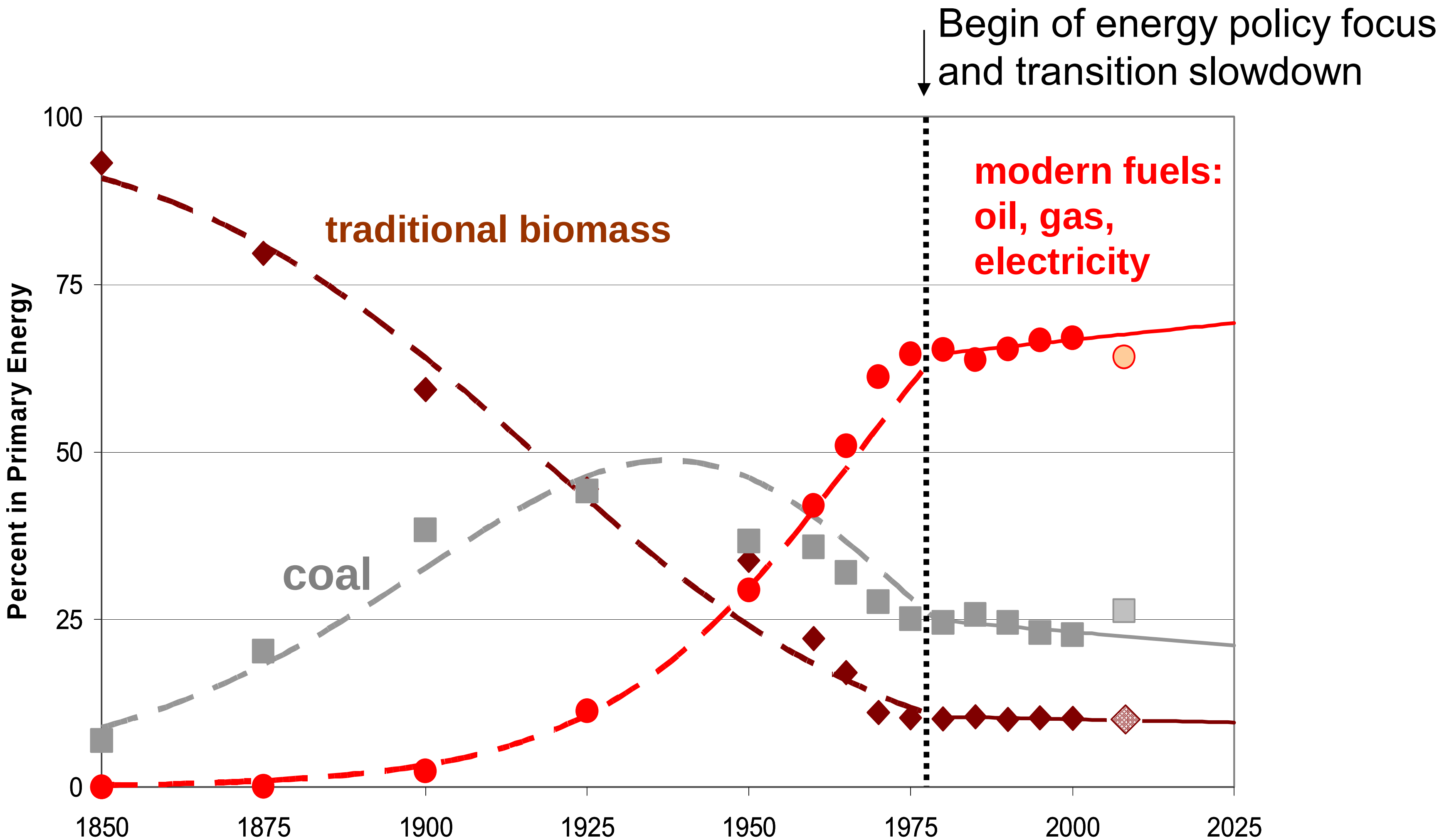
| category | technology | data for: | cumulative production (units) # | exp | period | learnin rate |
|---|---|---|---|---|---|---|
| energy end-use | Transitors | World | >1 | 10^18 | *1960-2010* | 40 |
| | DRAMs | World | >1 | 10^11 | *1975-2005* | 16 - 24 |
| | Automobiles | World | >2 | 10^9 | *1900-2005* | 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** |

**Source: Wilson et al., 2012**

# Lesson 5: Influence of Policies?

- No single hammer for all nails!
- Good evidence at micro- and meso scale (Dehli CNG buses, cat cars, UK smokeless zones)
- Key for policy successes: patience, predictability, credibility, alignment, documentation of success
- Successful transitions: repeat of established patterns along the energy ladder (more energy services via higher exergy quality carriers), no large-scale "leapfrogging" examples yet
- Global scale: significant transition slowdown since 1970s (conflicting policy objectives?)

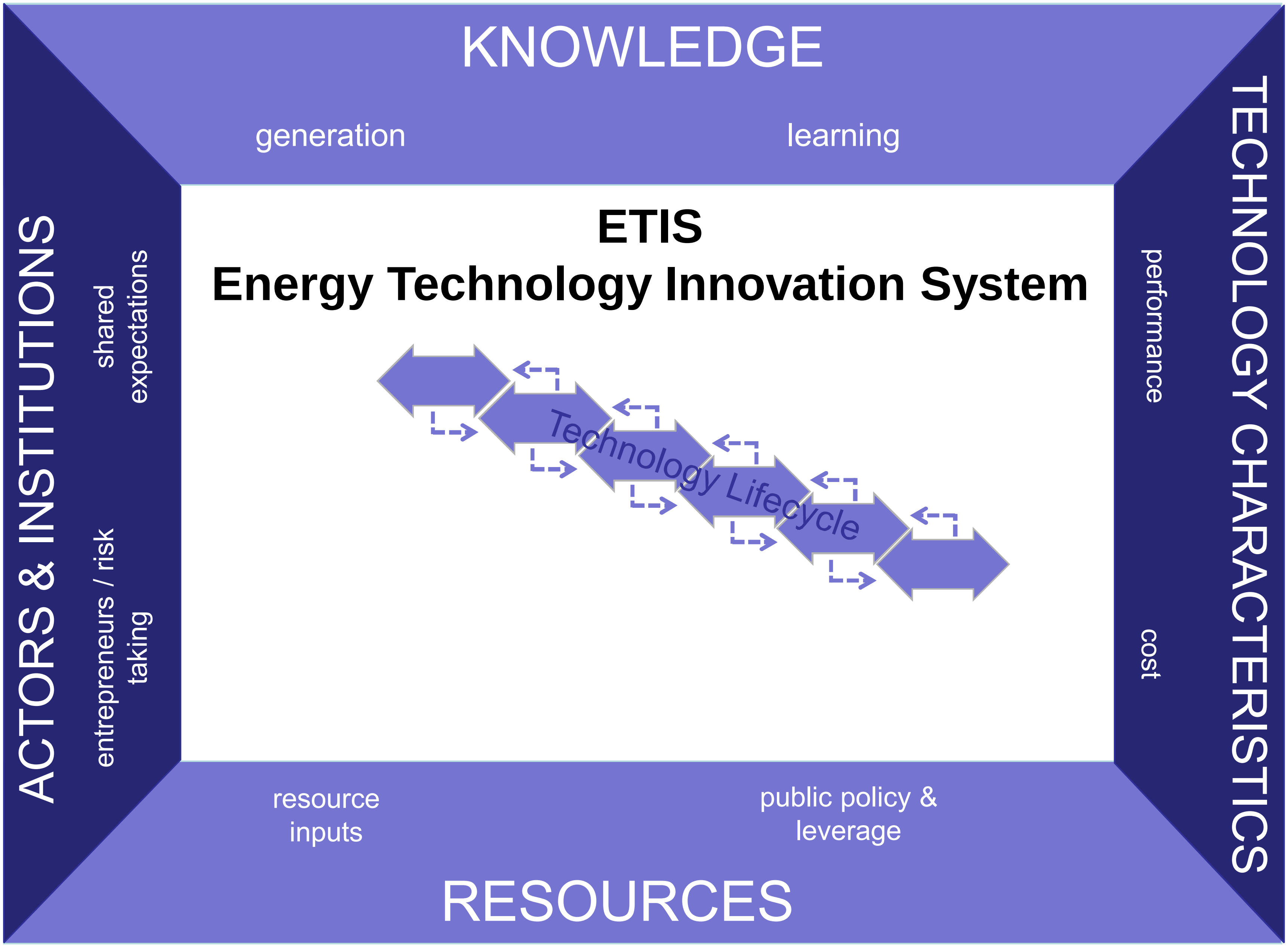
# World - Primary Energy Substitution

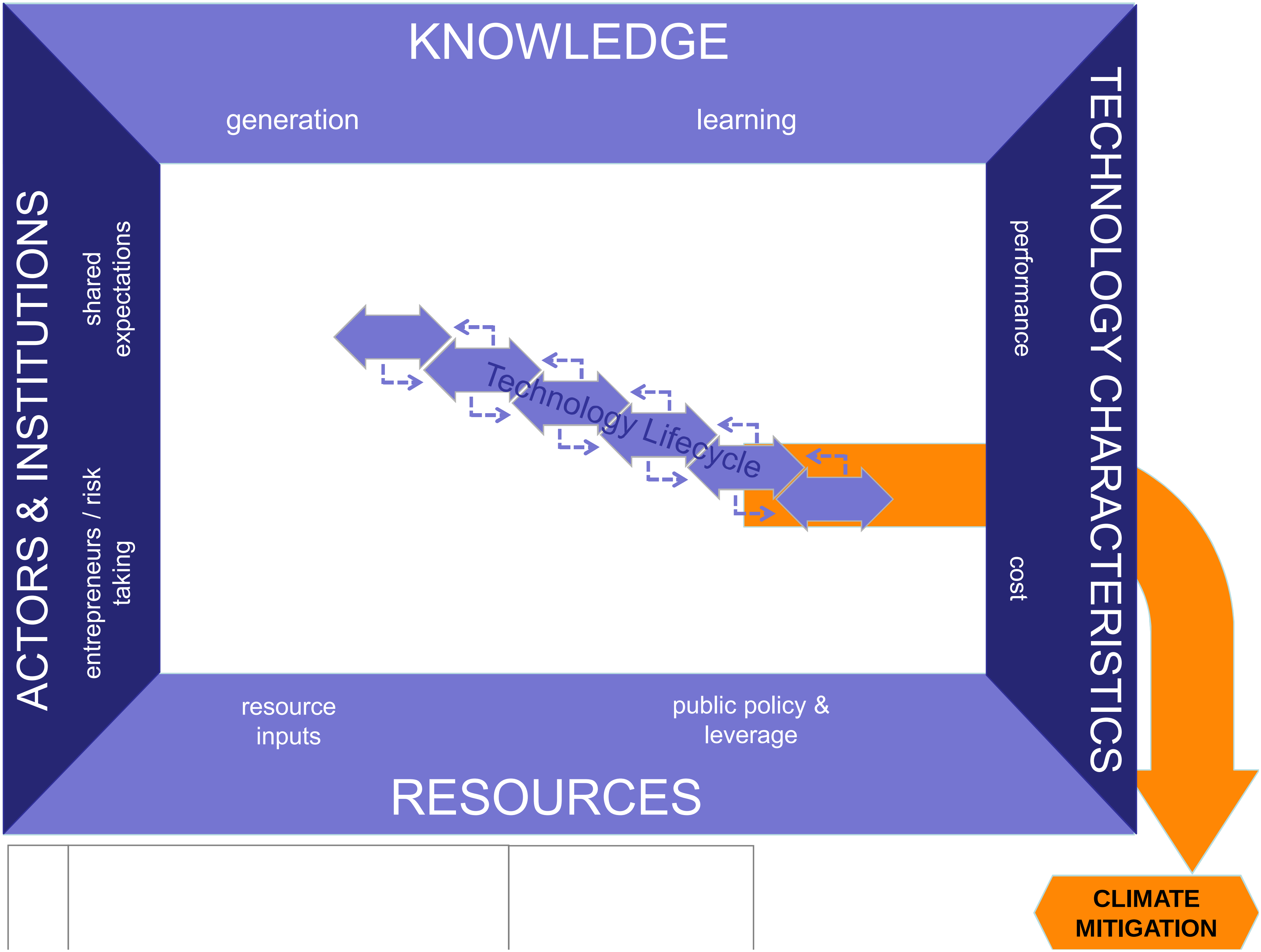



Source: GEA KM24, 2012

# A Next, Sustainability Energy Transition?

- <u>Unfavorable</u> baseline (<u>no</u> structural change)
- Innovation systems (GEA **ETIS**) <u>broken</u>:
  - portfolio bias (efficiency short-rifted)
  - spillovers blocked (BRICs exclusion)
  - wrong policy framework: "demand pull" (only)
    ("cost buy down" leading to cost escalation)
- <u>Lack</u> of consistent, aligned, and holistic policies
  - "boom & bust" (stimulus vs. ITC phase-out)
  - lack of externality pricing
  - social returns ignored
    (despite "green growth" rhetoric)


KNOWLEDGE
generation
learning
ETIS
Energy Technology Innovation System
Technology Lifecycle
ACTORS & INSTITUTIONS
shared expectations
entrepreneurs / risk taking
TECHNOLOGY CHARACTERISTICS
performance
cost
resource inputs
public policy & leverage
RESOURCES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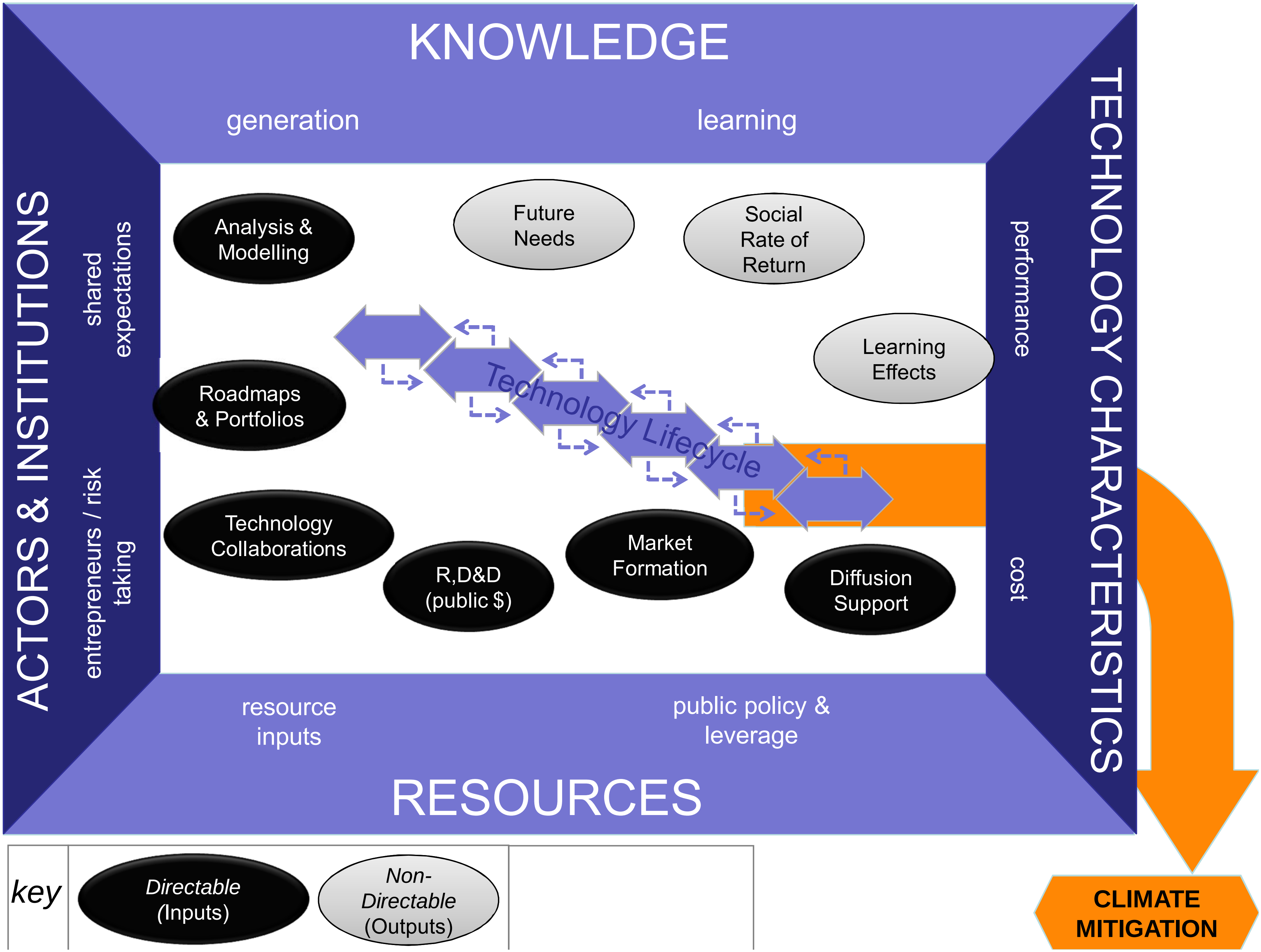
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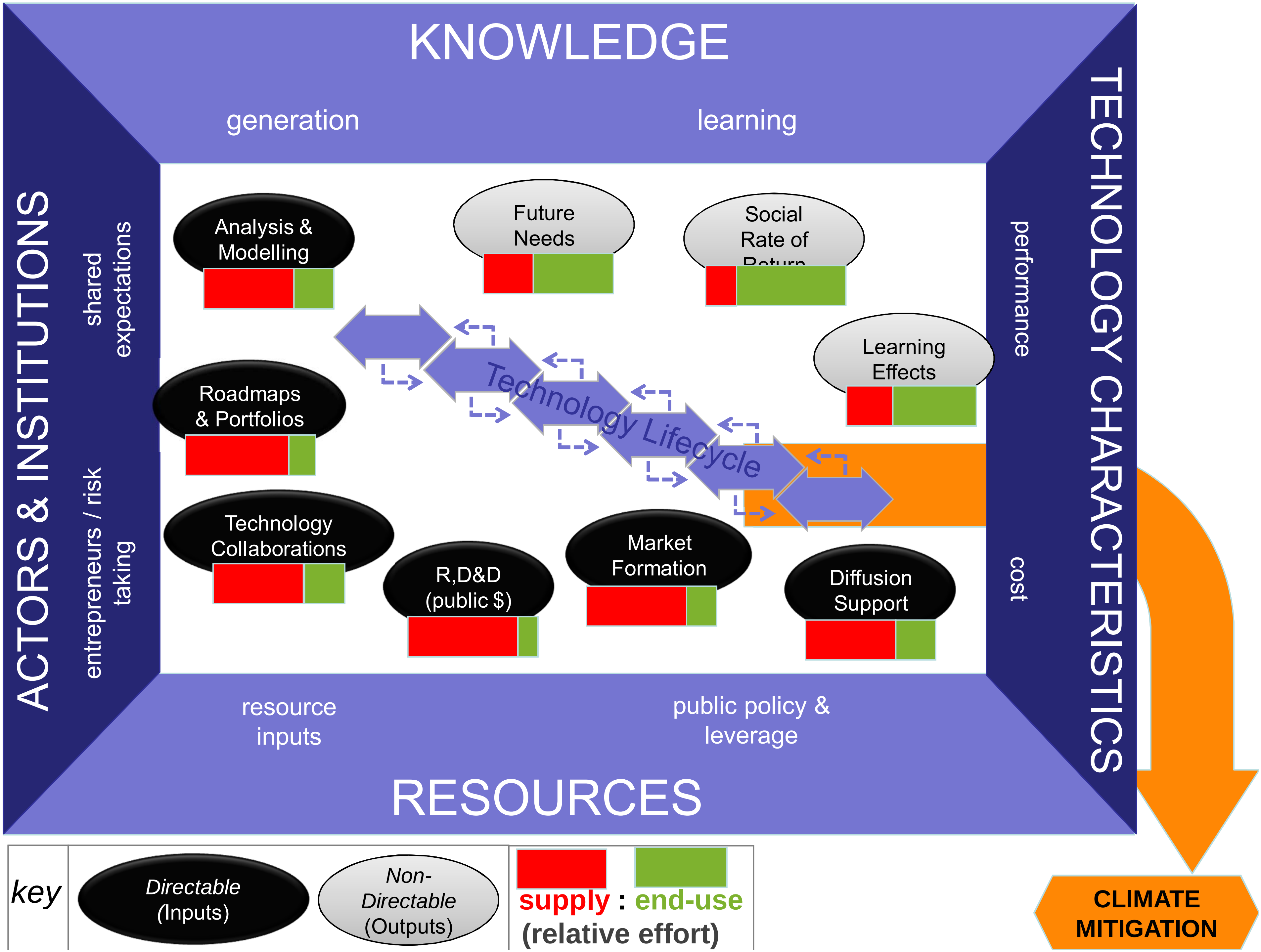
cost
Analysis & Modelling
Future Needs
Social Rate of Return
Learning Effects
Roadmaps & Portfolios
Technology Lifecycle
Technology Collaborations
R,D&D (public $)
Market Formation
Diffusion Support
resource inputs
public policy & leverage
RESOURCES
key
Directable (Inputs)
Non-Directable (Outputs)
CLIMATE MITIGATION



KNOWLEDGE
generation
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shared expectations
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TECHNOLOGY CHARACTERISTICS
performance
cost
RESOURCES
resource inputs
public policy & leverage
Analysis & Modelling
Future Needs
Social Rate of Return
Learning Effects
Roadmaps & Portfolios
Technology Lifecycle
Technology Collaborations
R,D&D (public $)
Market Formation
Diffusion Support
key
Directable (Inputs)
Non-Directable (Outputs)
supply : end-use
(relative effort)
CLIMATE MITIGATION

# References & Additional Reading


- Global Energy Assessment (GEA), 2012,
  Chapter 1. Energy Primer,
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  Online at: www.globalenergyassessment.org
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