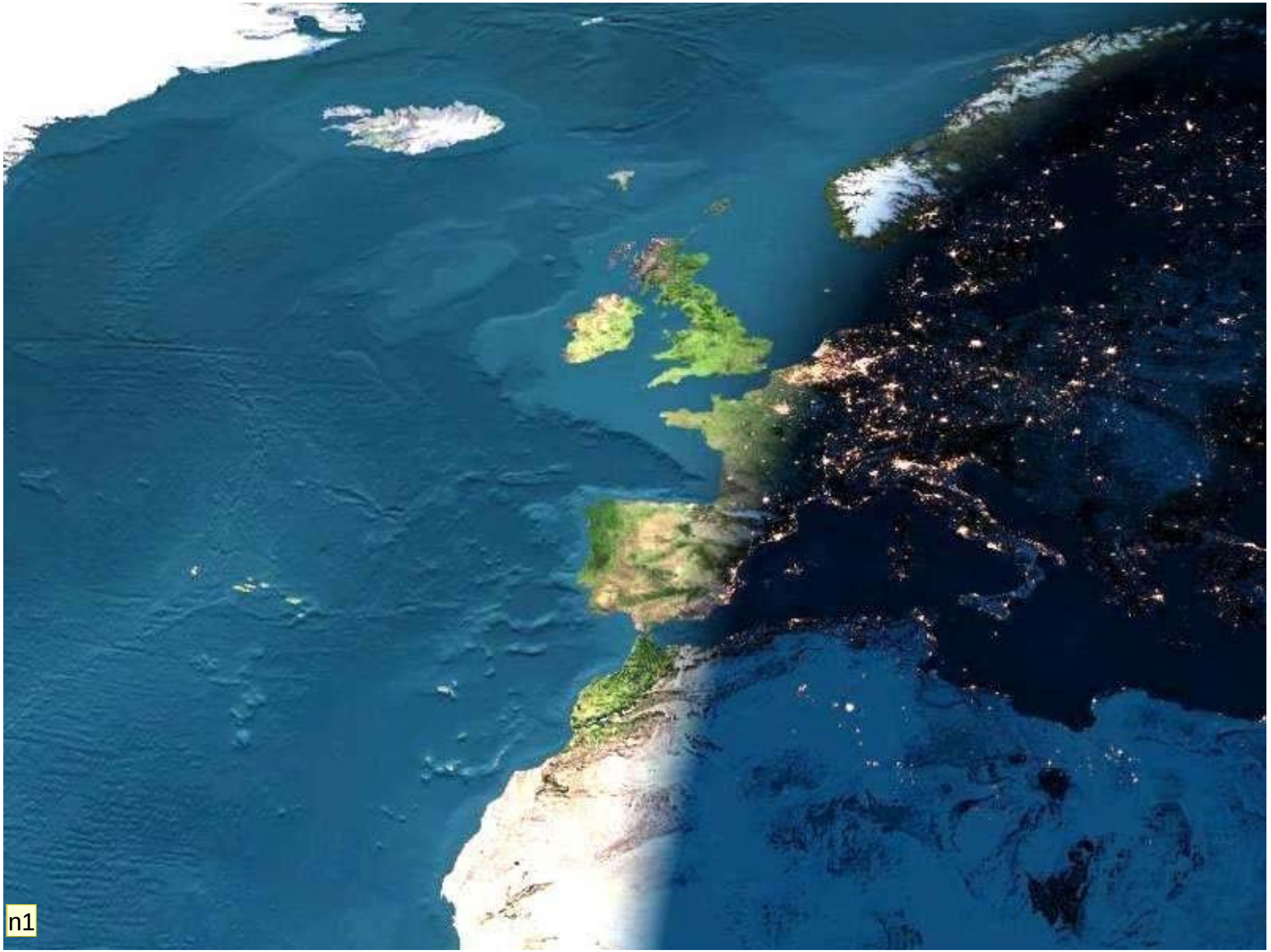
# Modeling Dynamics and Uncertainty of Technological Change

Nebojša Nakićenović
International Institute for Applied Systems Analysis
Technische Universität Wien
naki@iiasa.ac.at


Modeling Technological Innovation Workshop
Santa Fe Institute, Santa Fe, New Mexico — 13-15 August 2008

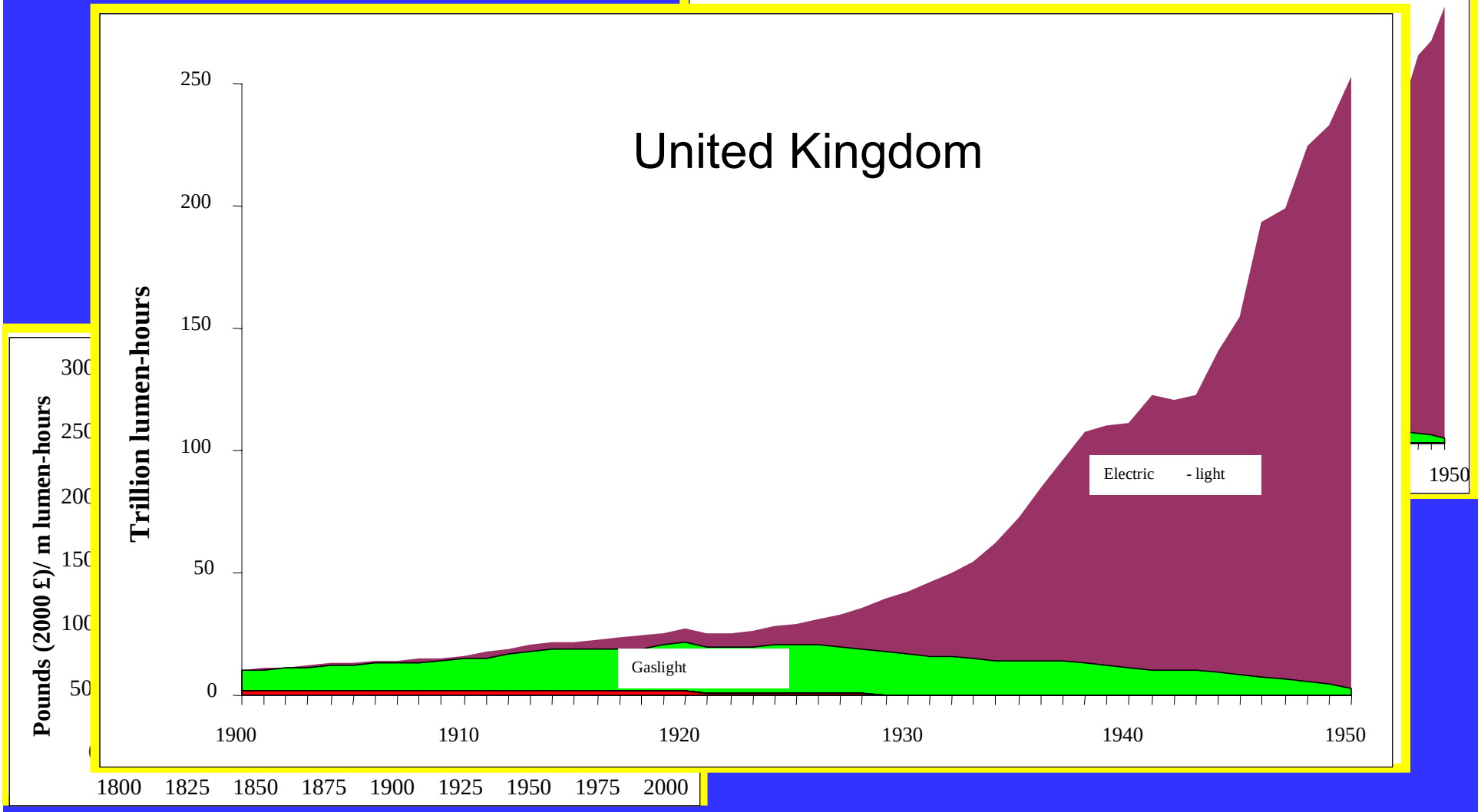

n1

## Slide 2

**n1**

This Picture of the North Pole is
Composed from Satellite Photos:
Here is the file:  n08d-earthcam-26778TN.jpg
Courtesy of the authors at
www.earthcam.com
naki; 30.10.2007

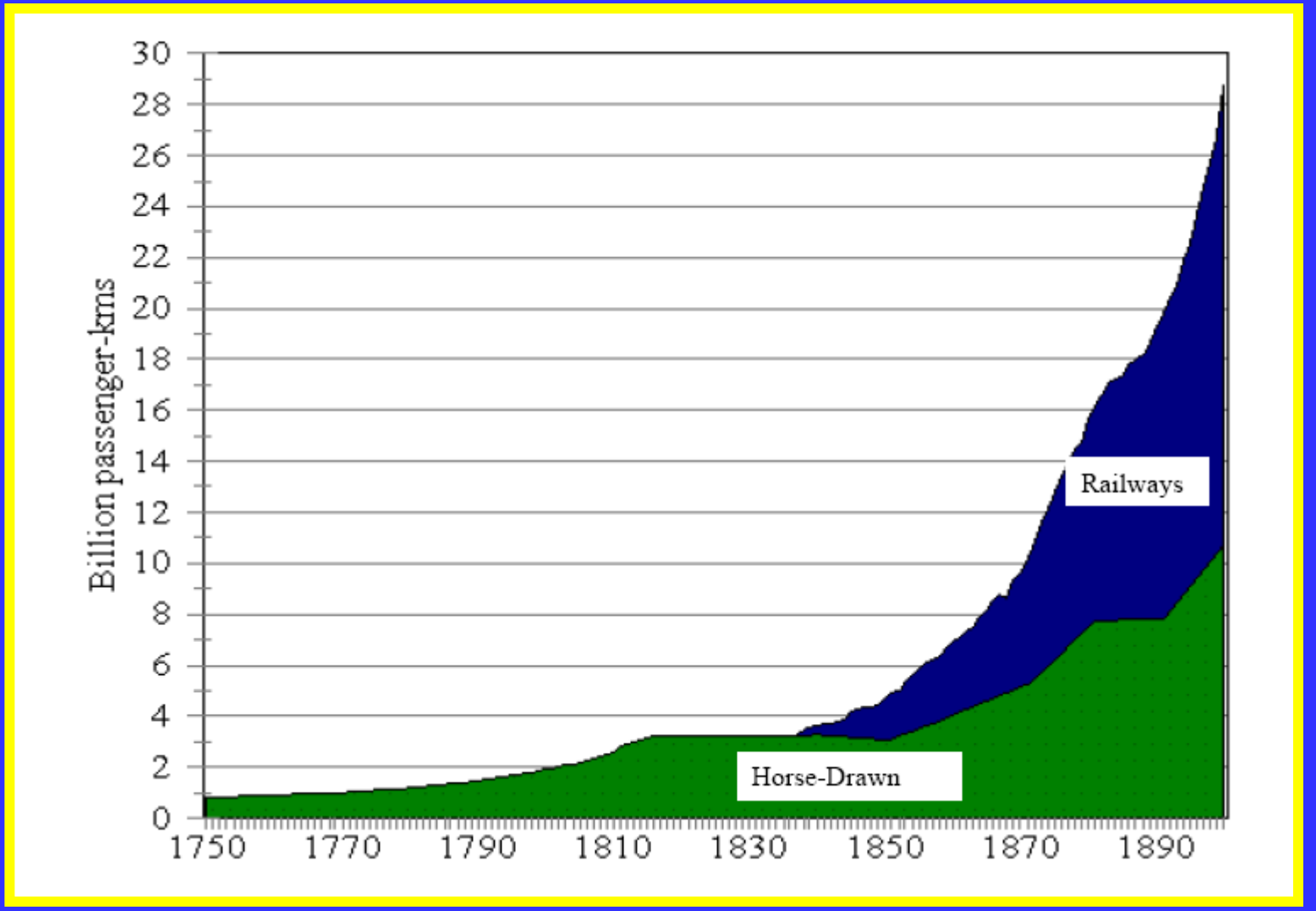
# The Example of Lighting



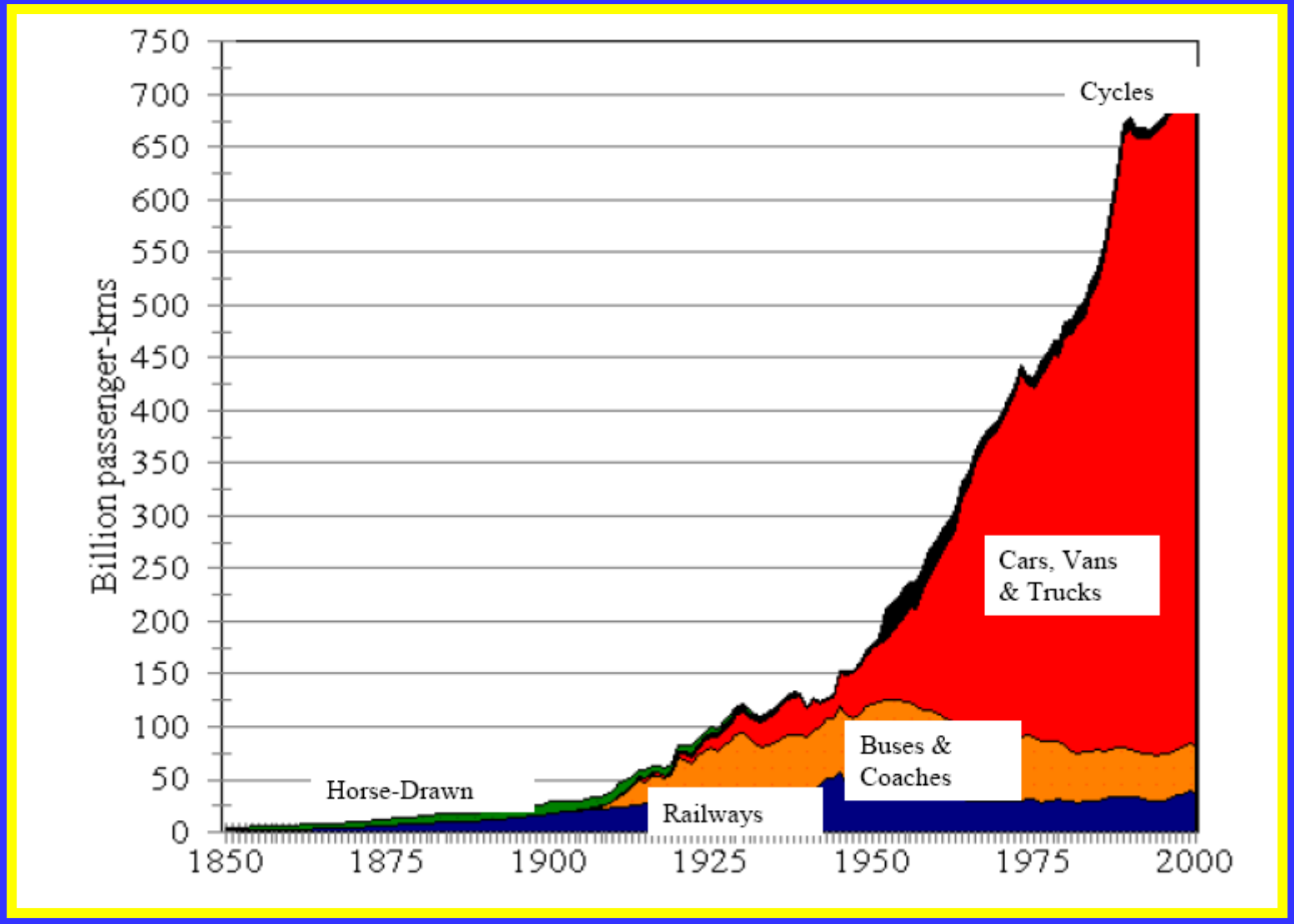
# Technological Change: Dynamic, Cumulative, Systemic and Uncertain

- Incremental – gradual (continuous) and cumulative improvements
- Abrupt – radical, discontinuous and disruptive as “gales of creative destruction”

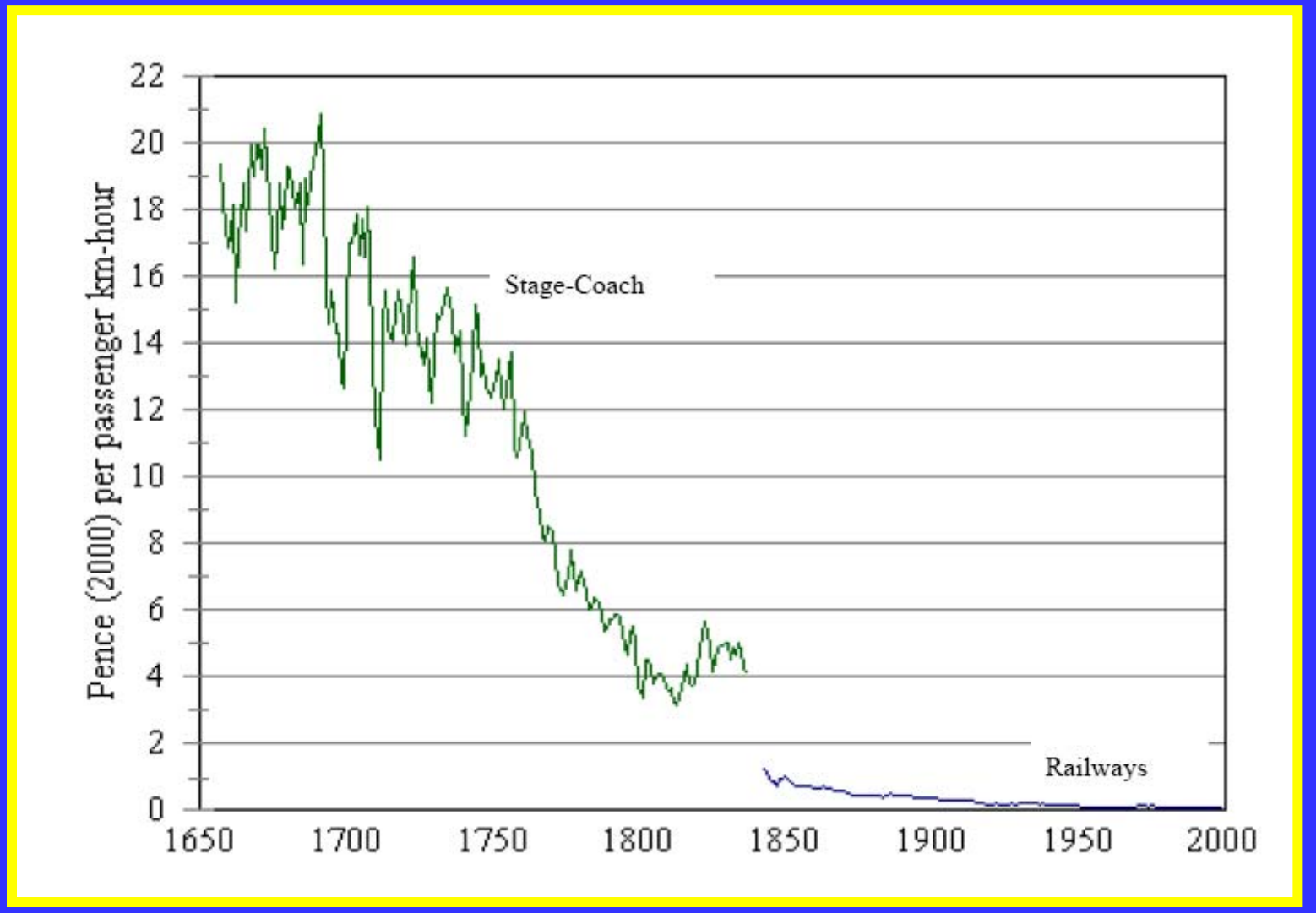
# Use of Passenger Transport
## (per passenger-kilometer)



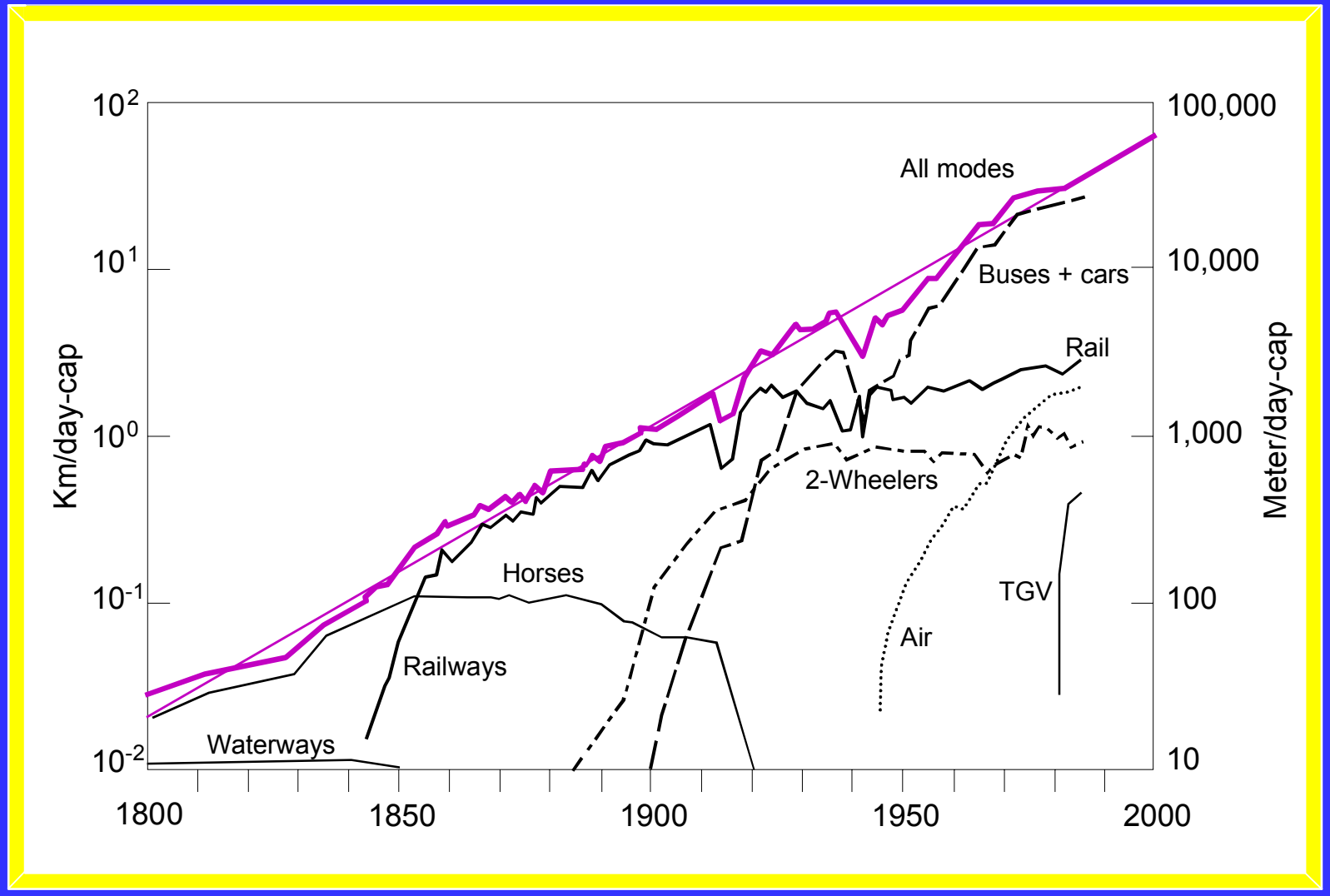
# Use of Passenger Transport
## (per passenger-kilometer)



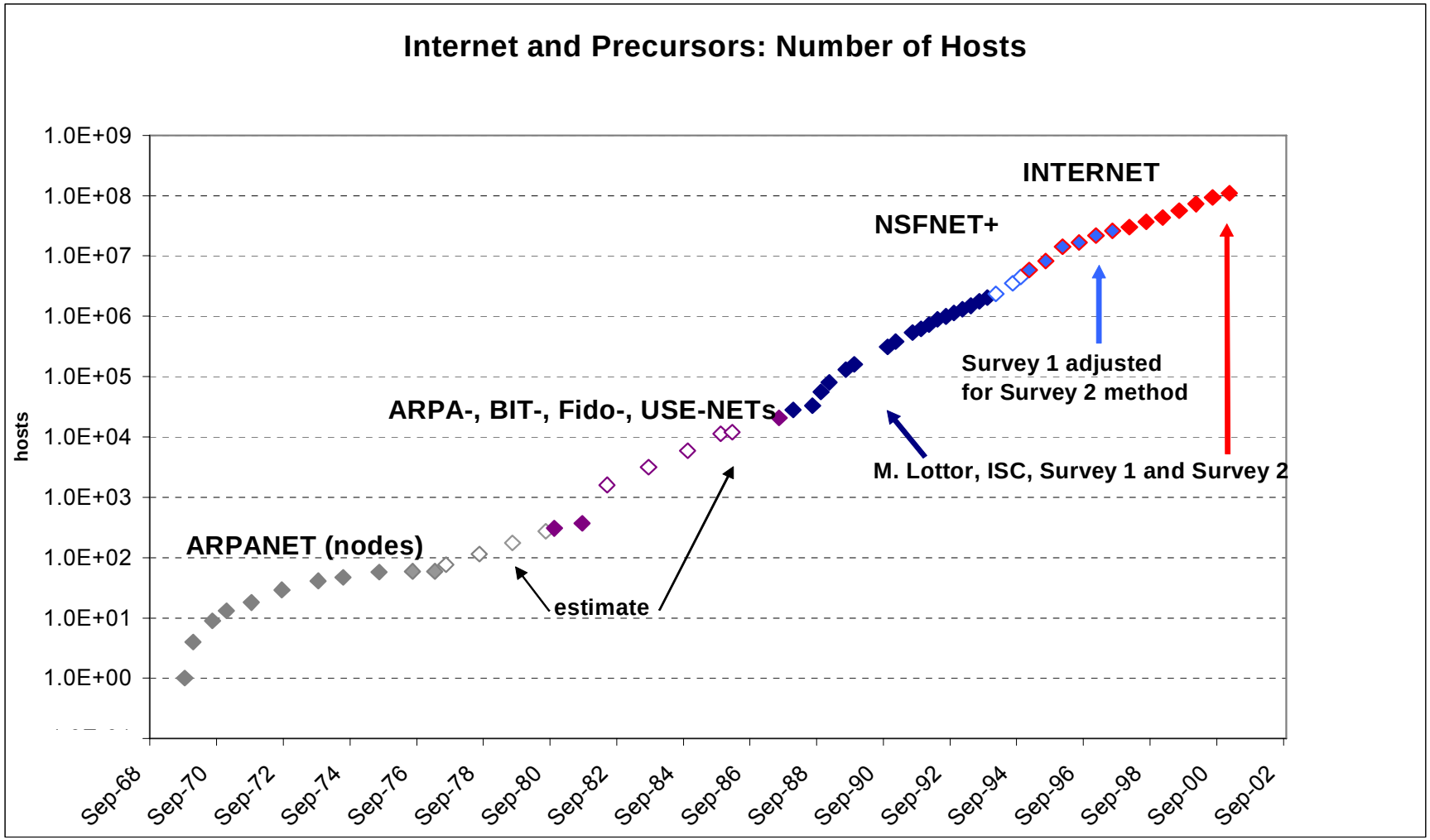
# Price of Passenger Transport
## (per passenger-kilometer-hour)



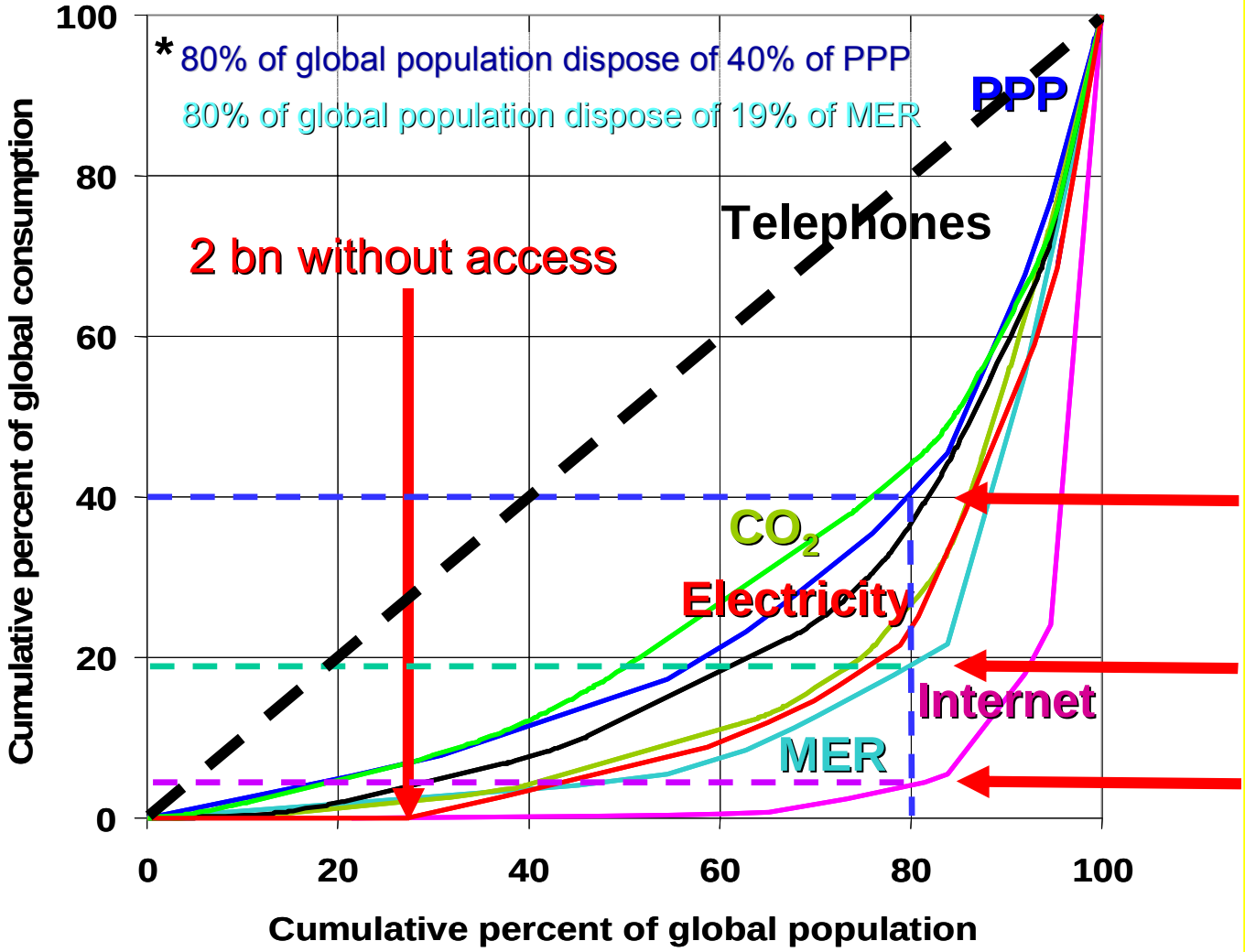
# France – Mobility by Travel Mode
## (passenger-kilometers per day per person)



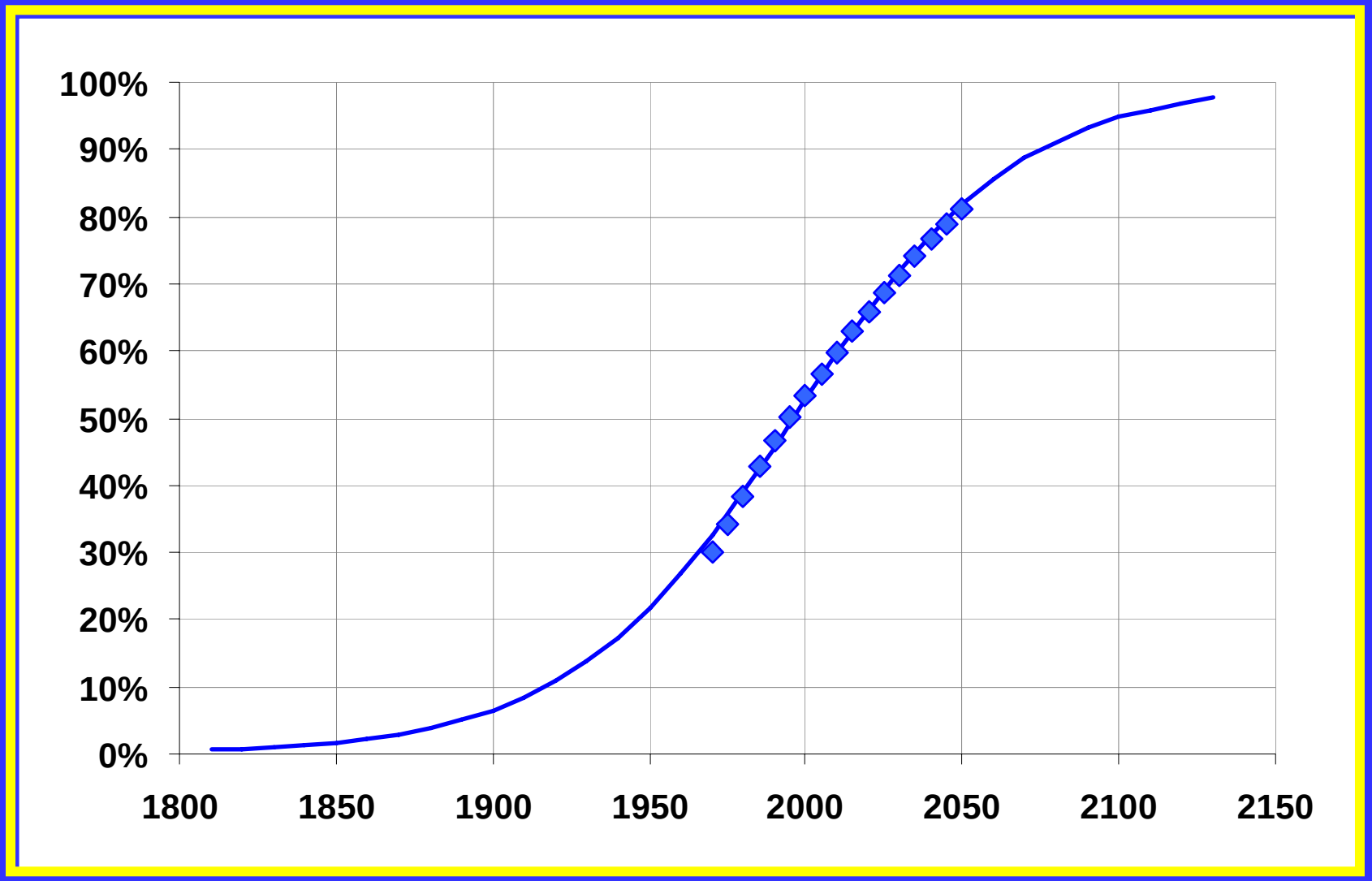
# Growth of Interconnectivity



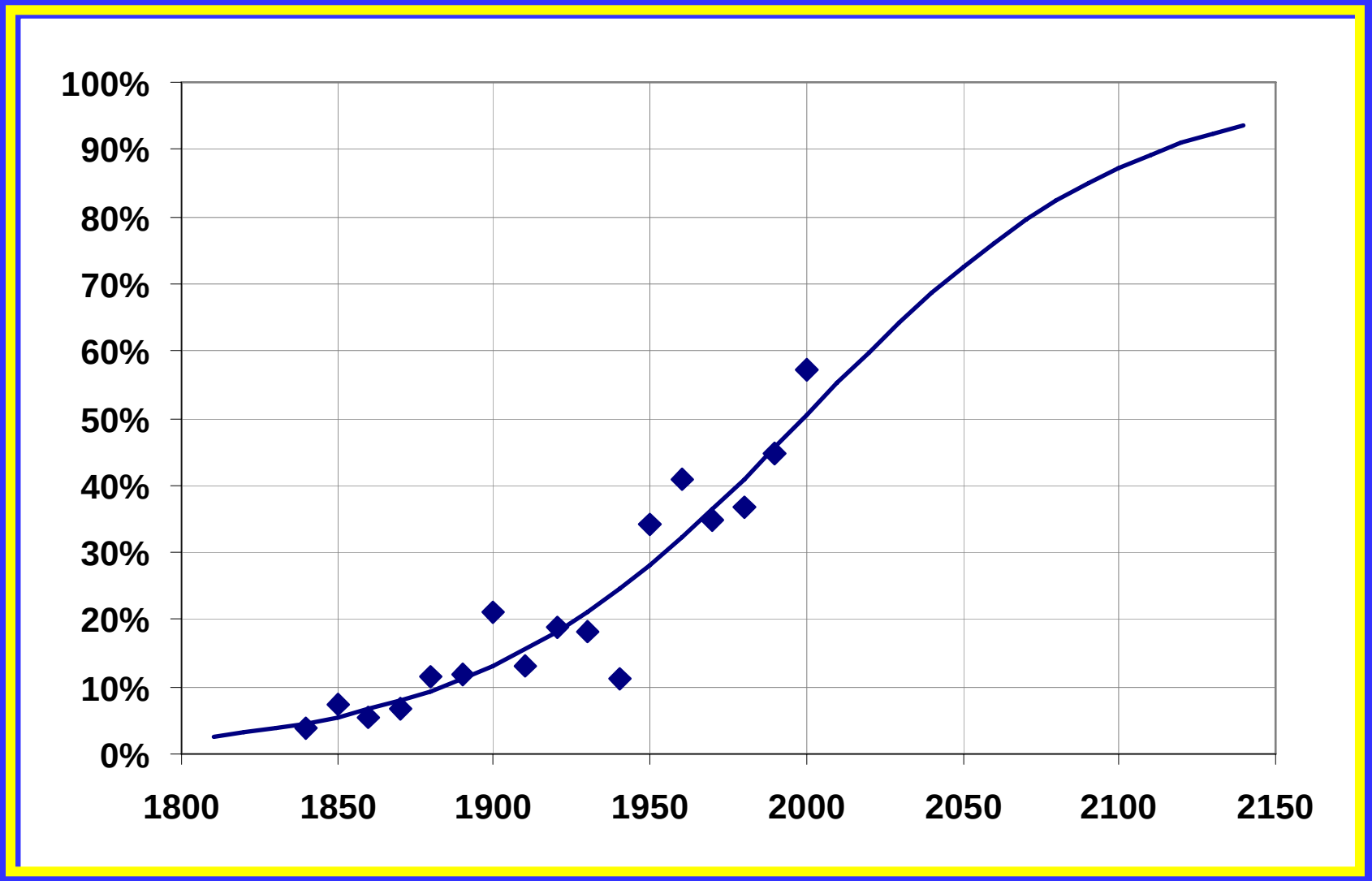
# Global Disparities



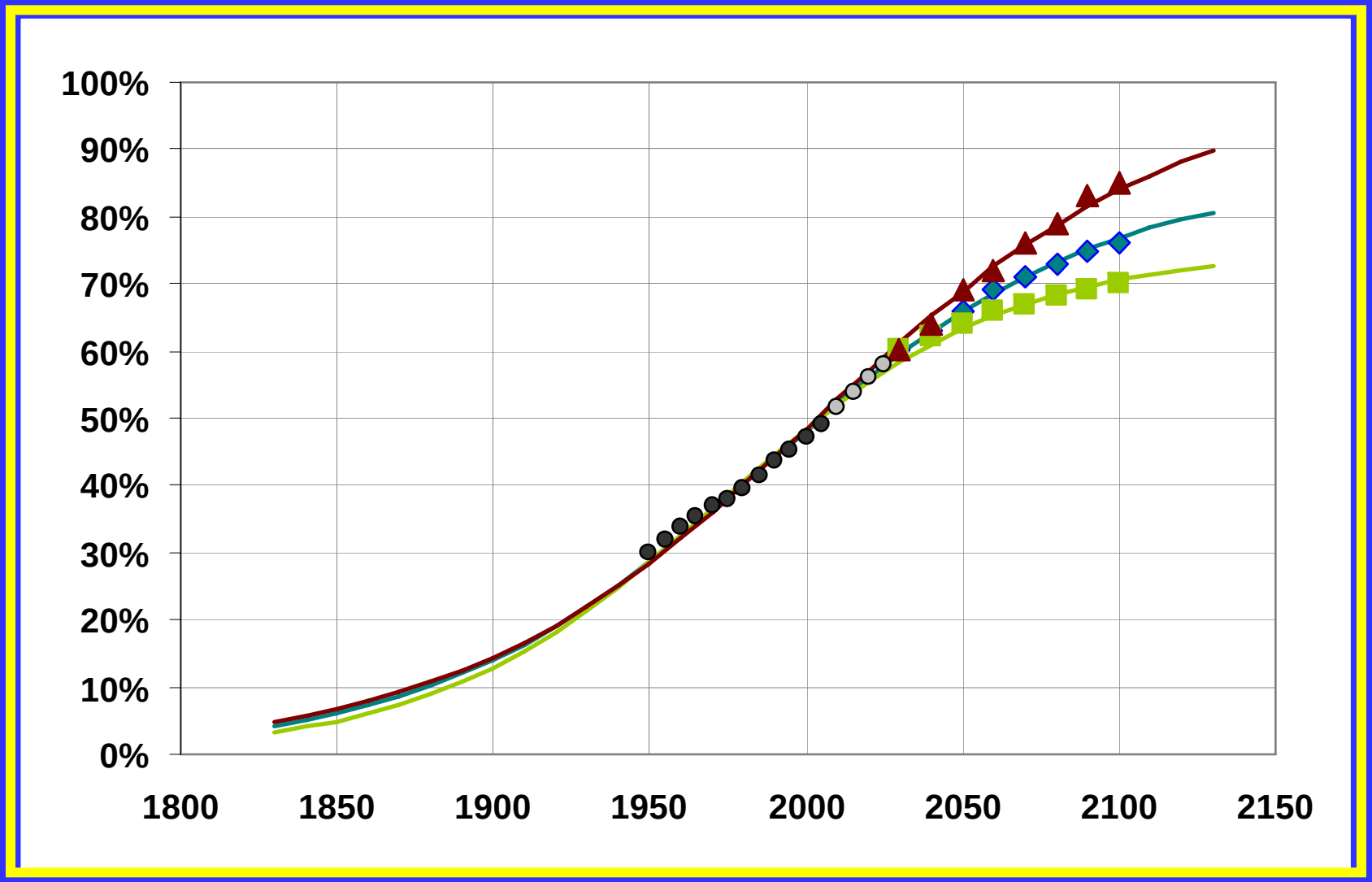
# Education


100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
1800
1850
1900
1950
2000
2050
2100
2150

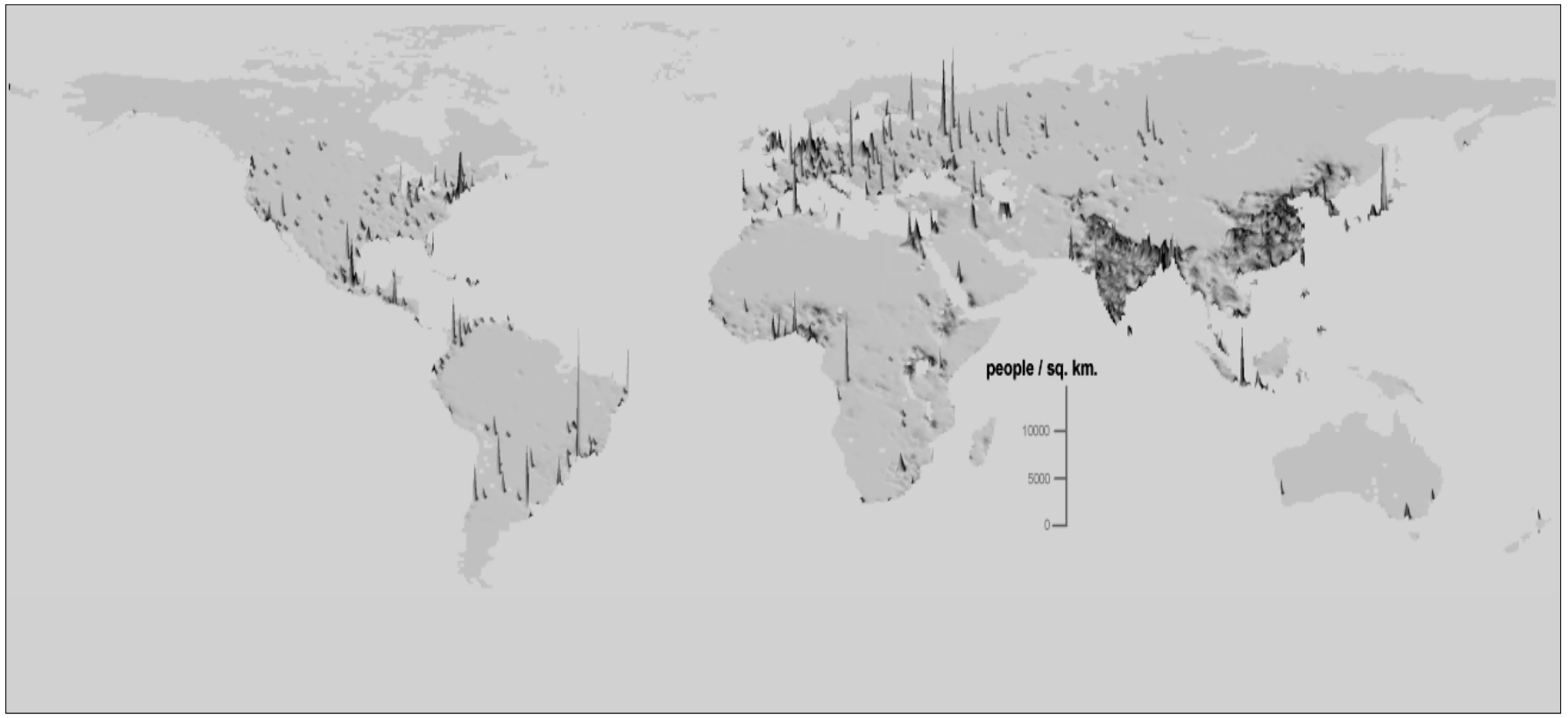
# Democratization



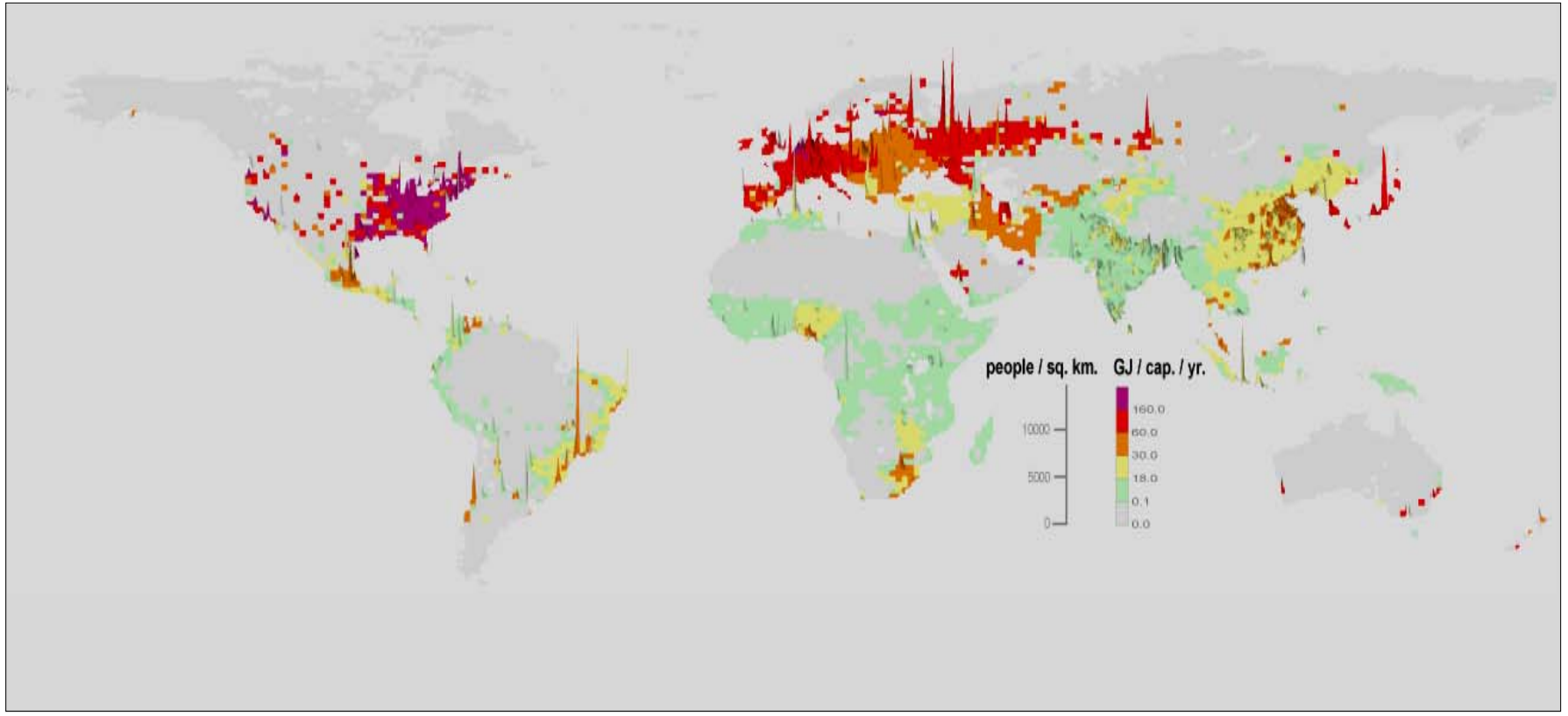
# Urbanization



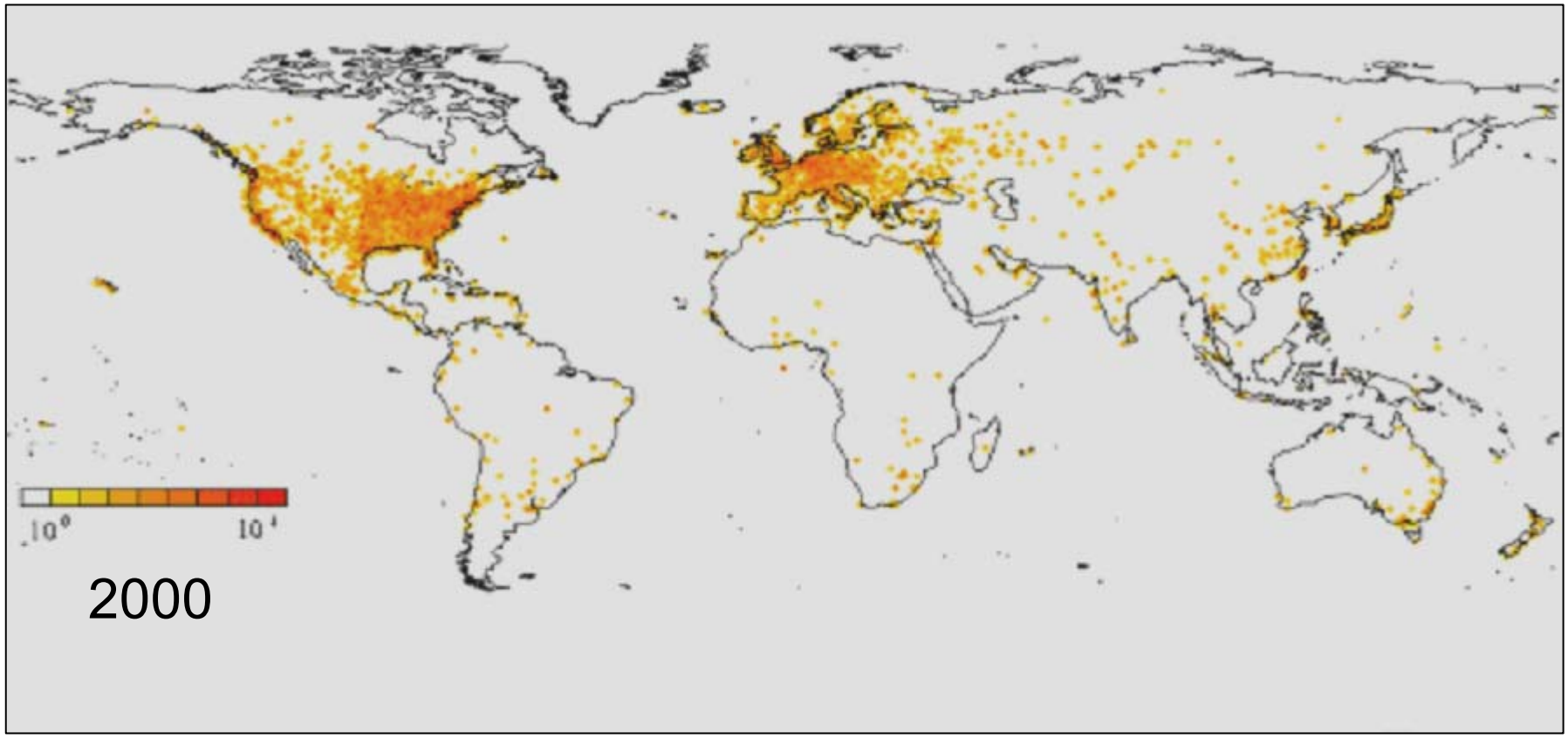
# Global Population



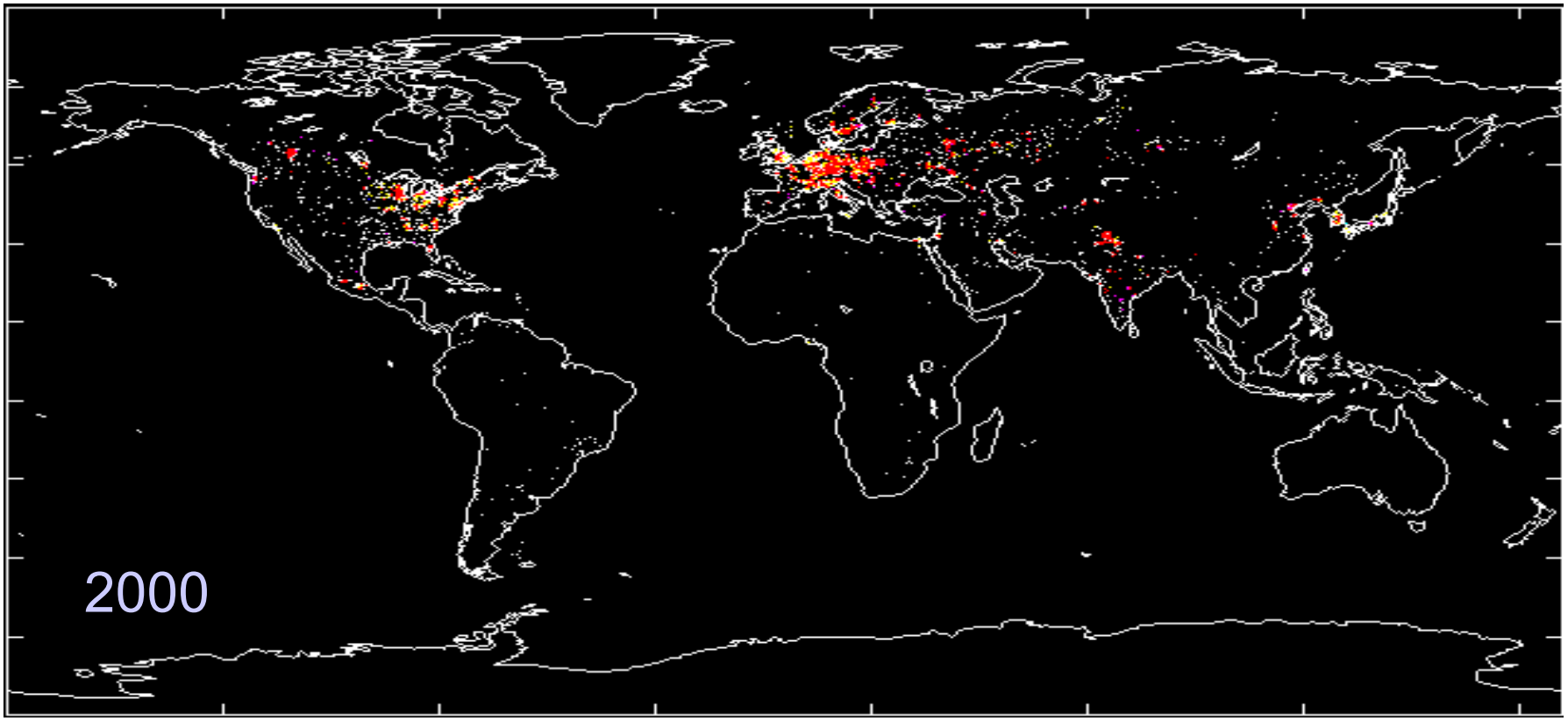
# Global Final Energy



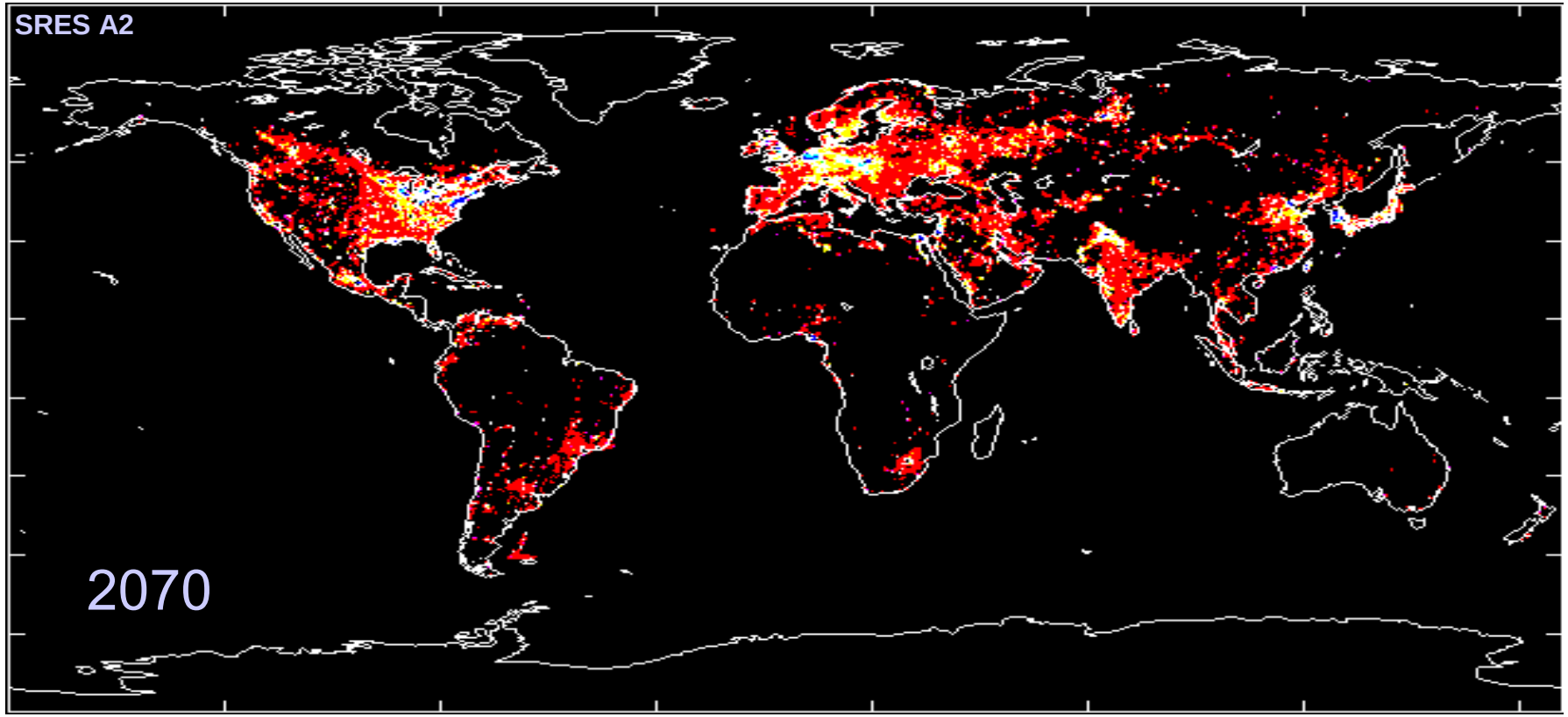
# Internet



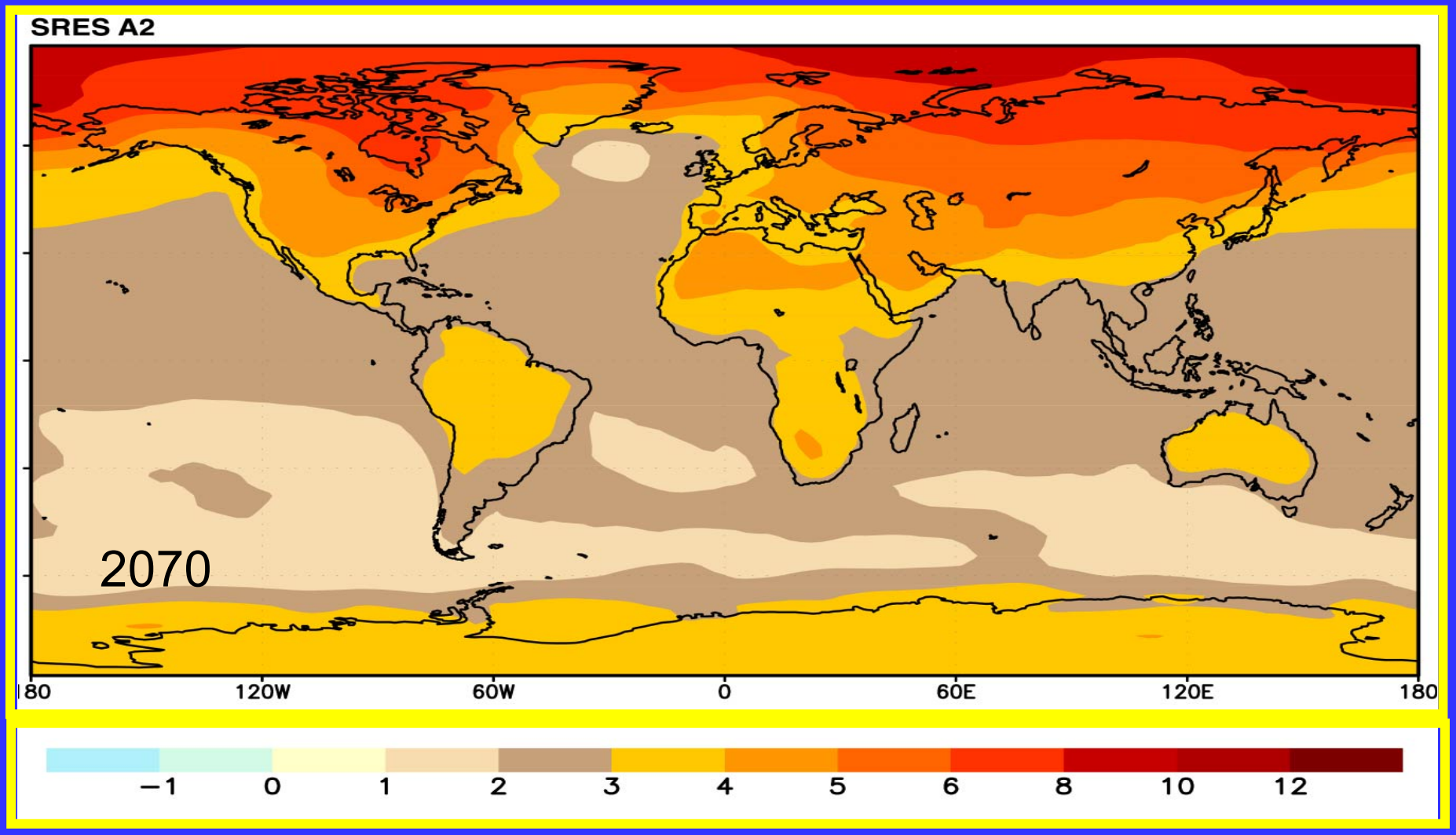
# Night Lights



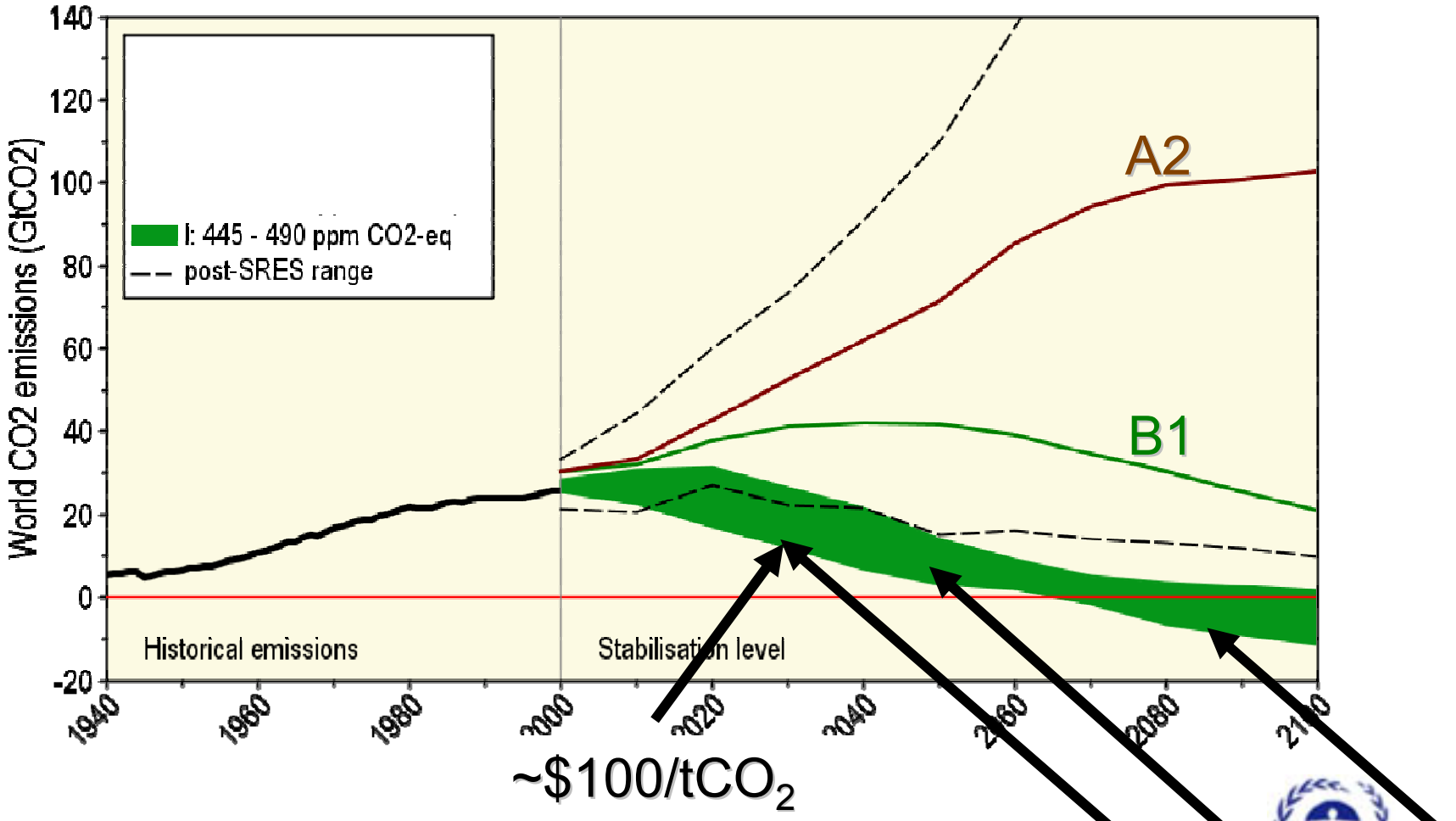
# Night Lights



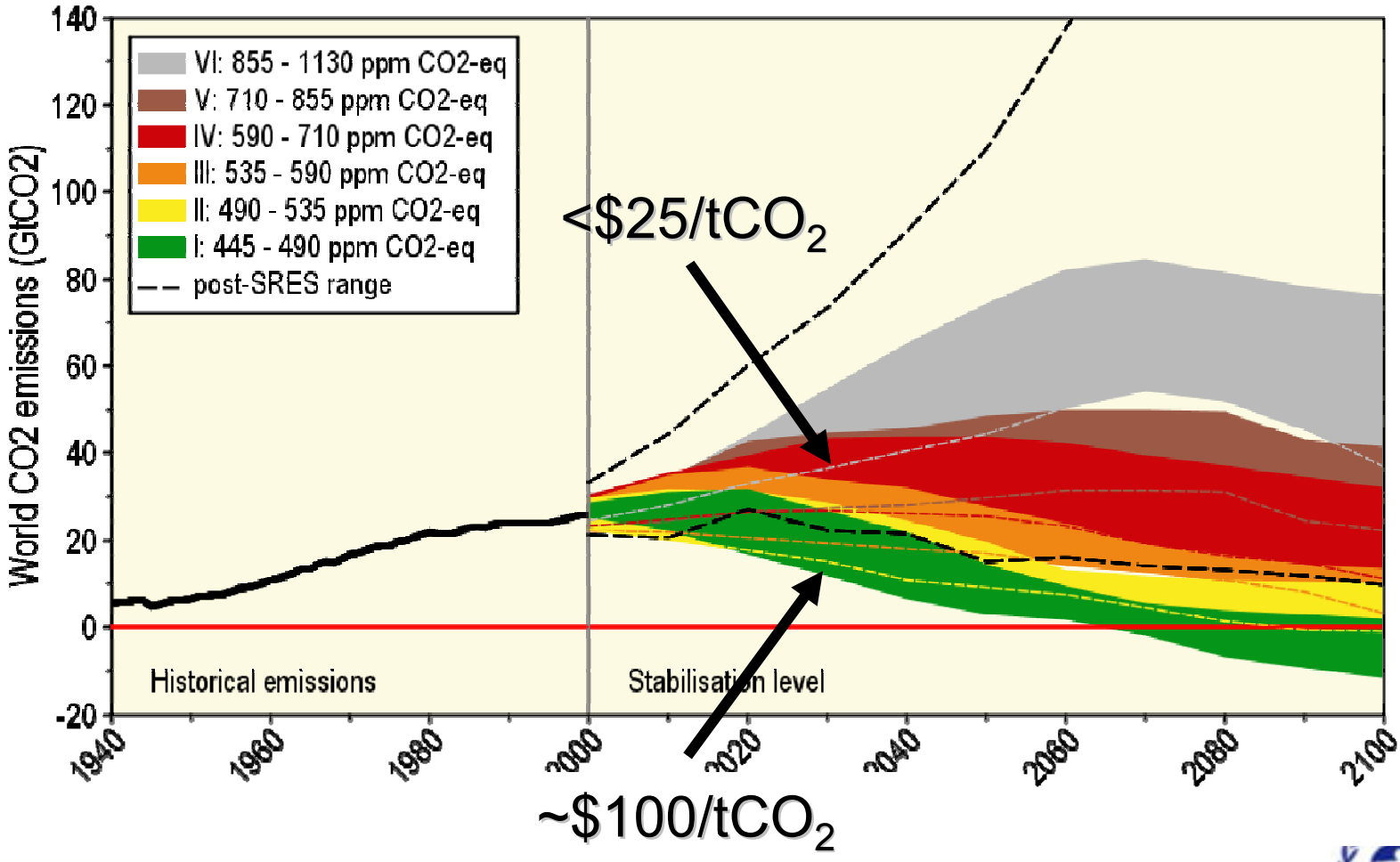
# Δ Temperature



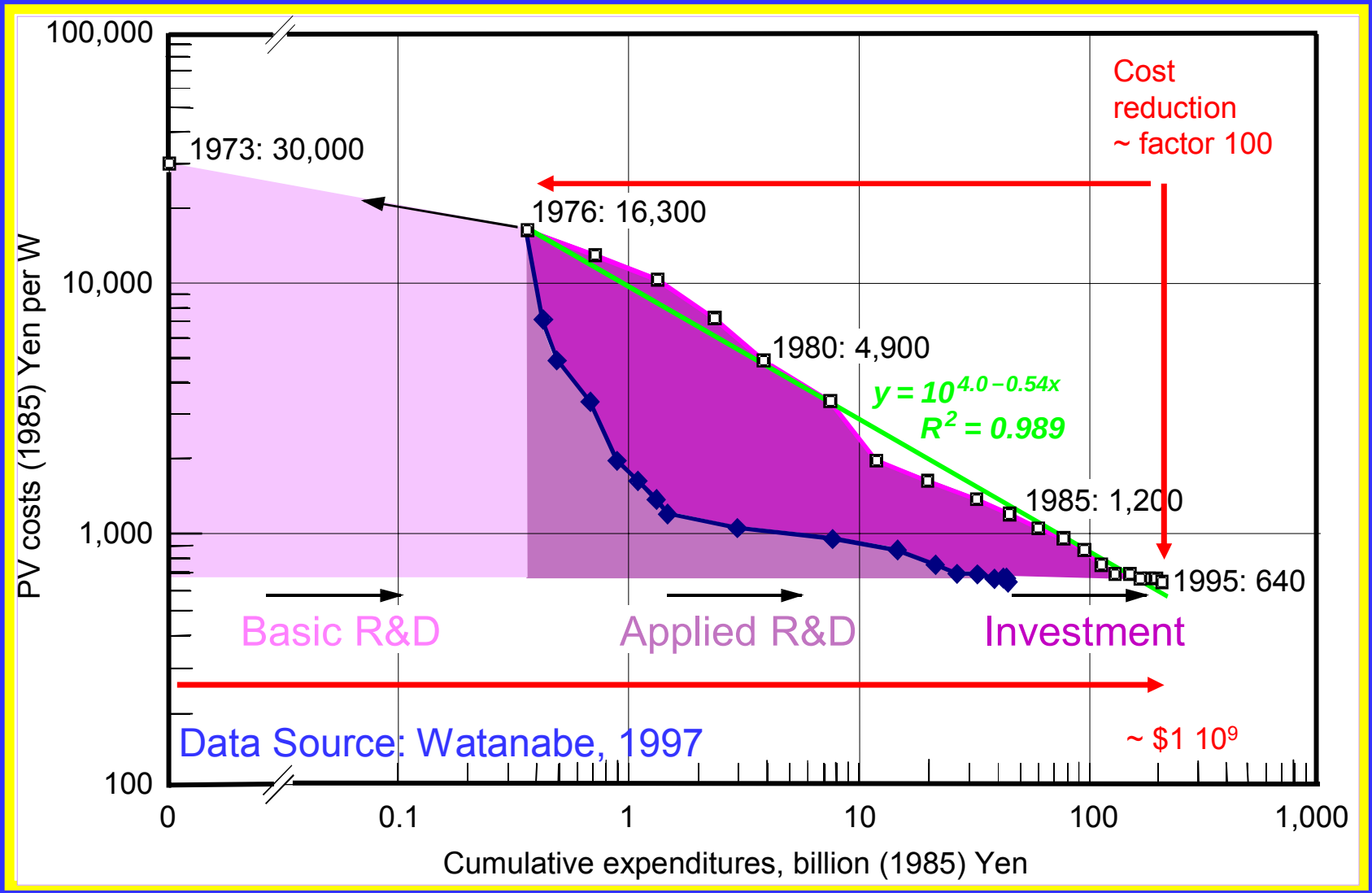
# Long-Term Stabilization Profiles



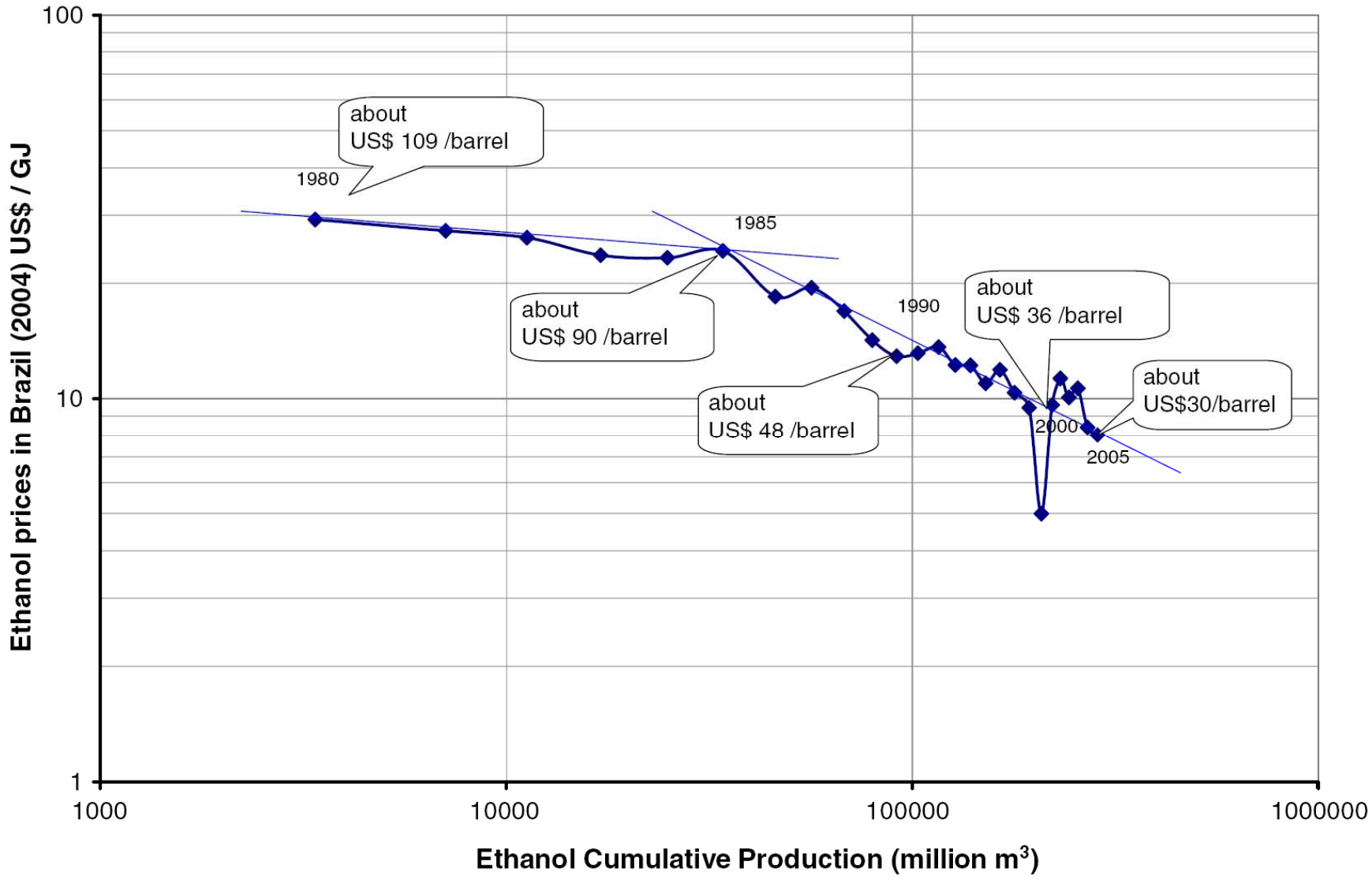
# Long-Term Stabilization Profiles



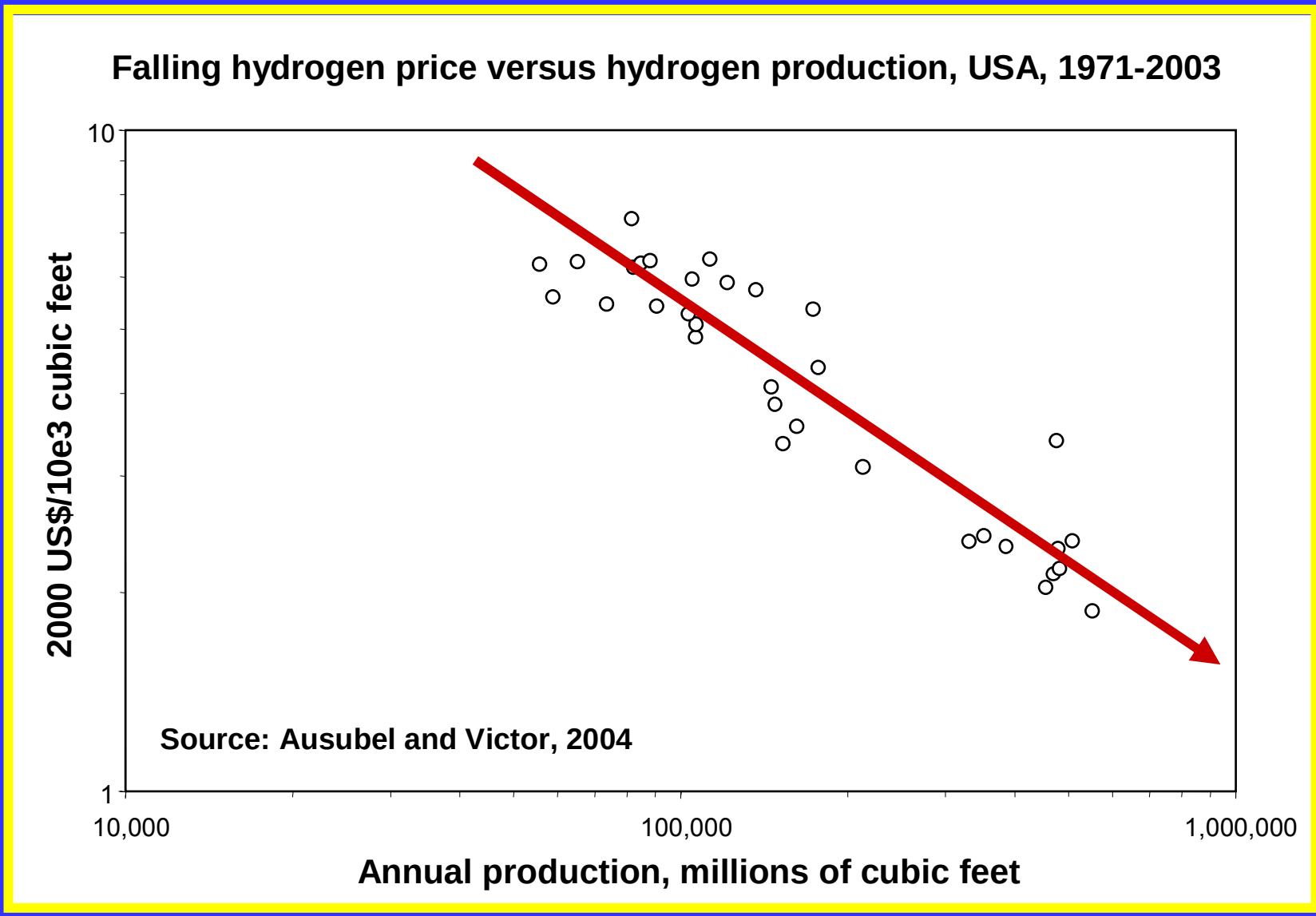
# Japan - PV Costs vs. Expenditures



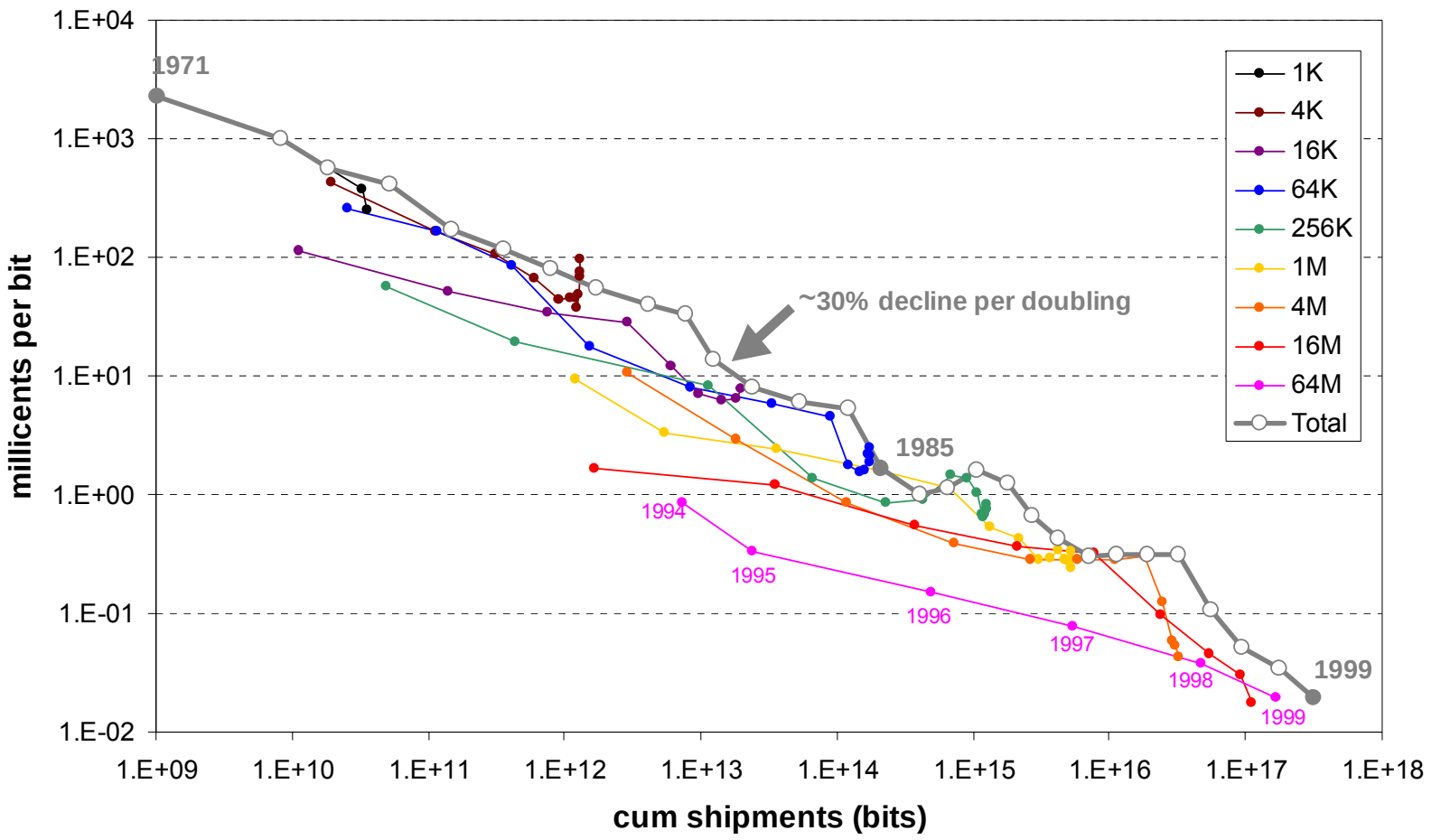
# Ethanol Learning Curve



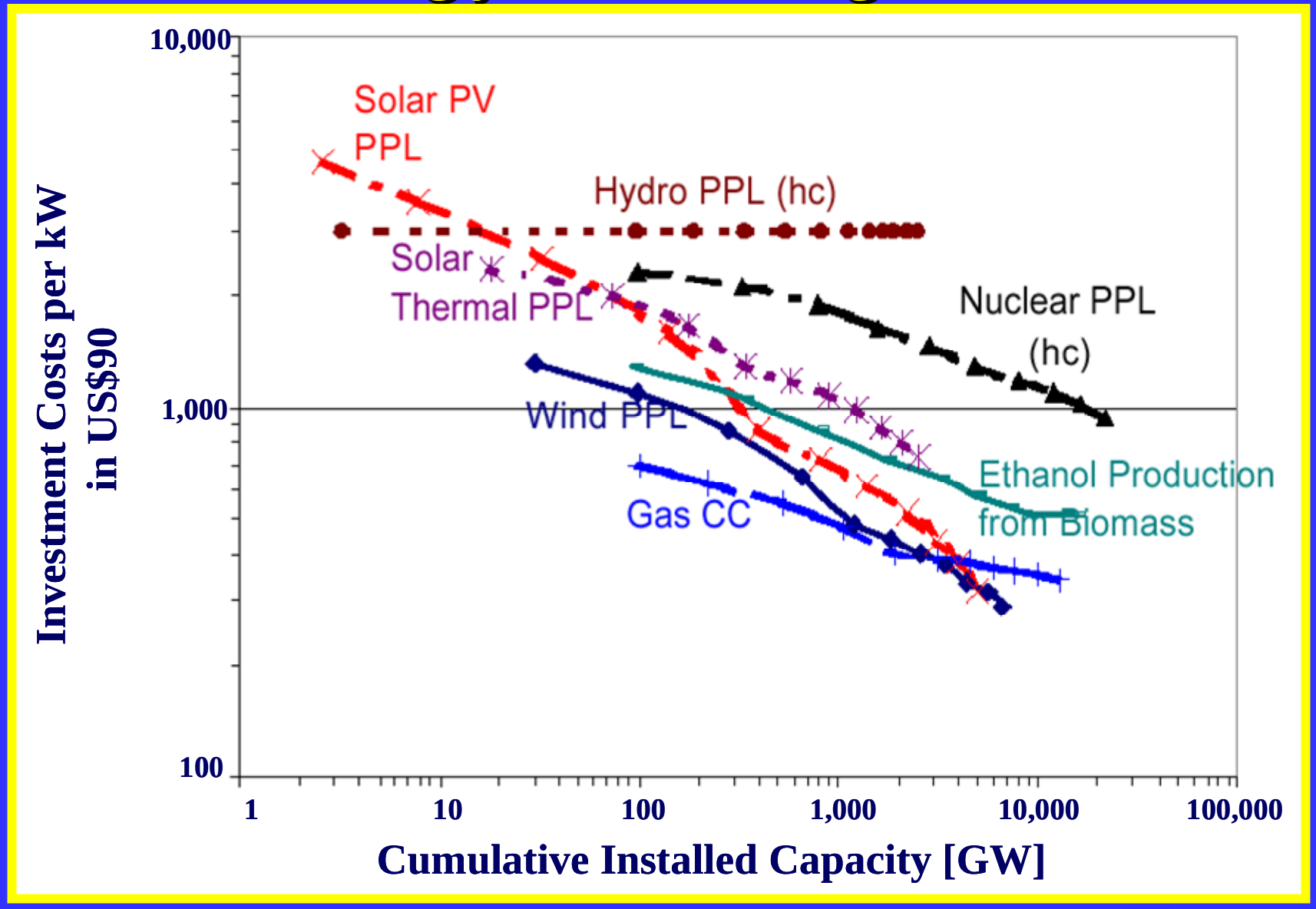
# Hydrogen Buy-Down a Learning Curve



# DRAM Prices and Market Growth

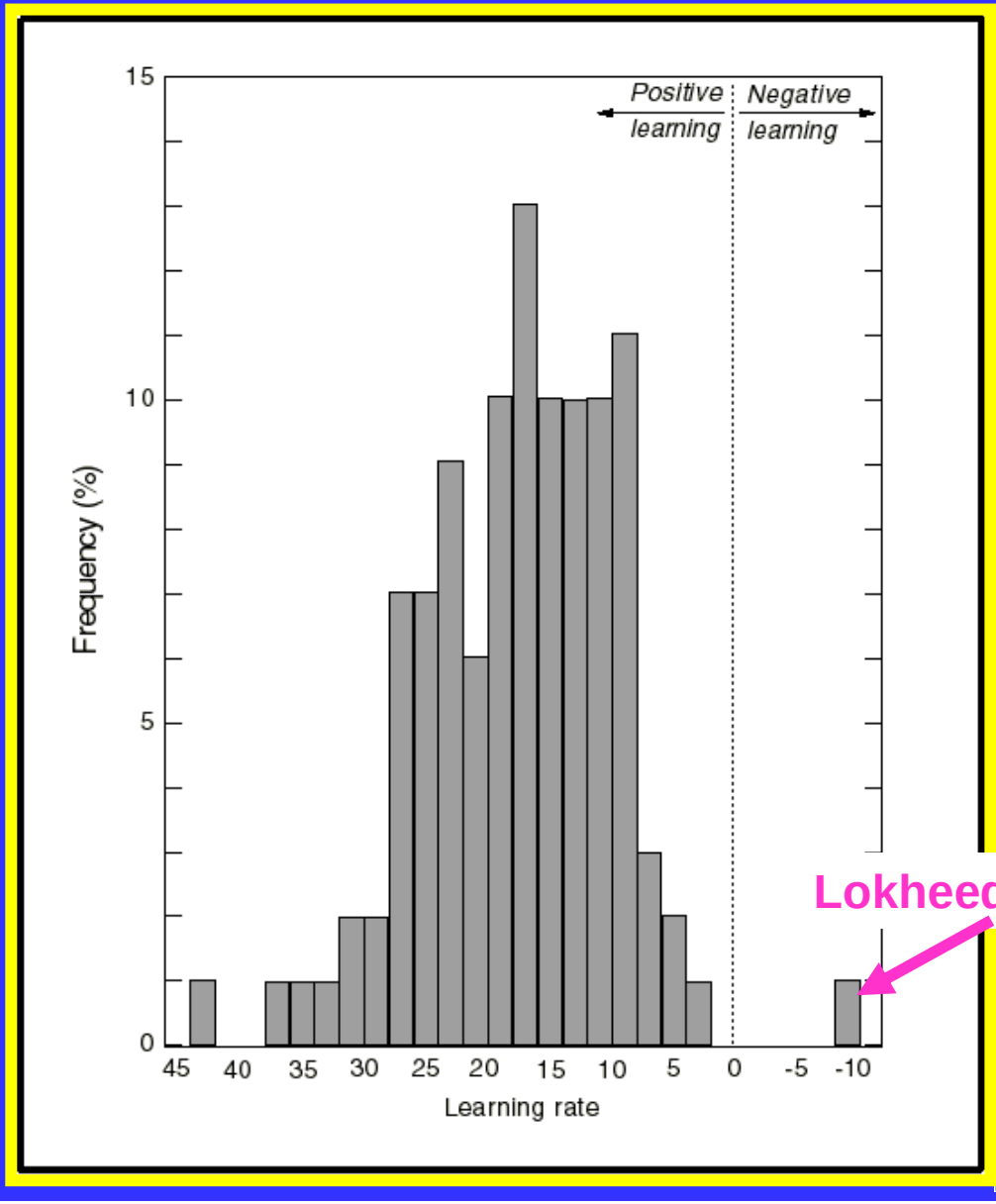


# Technology Learning in SRES

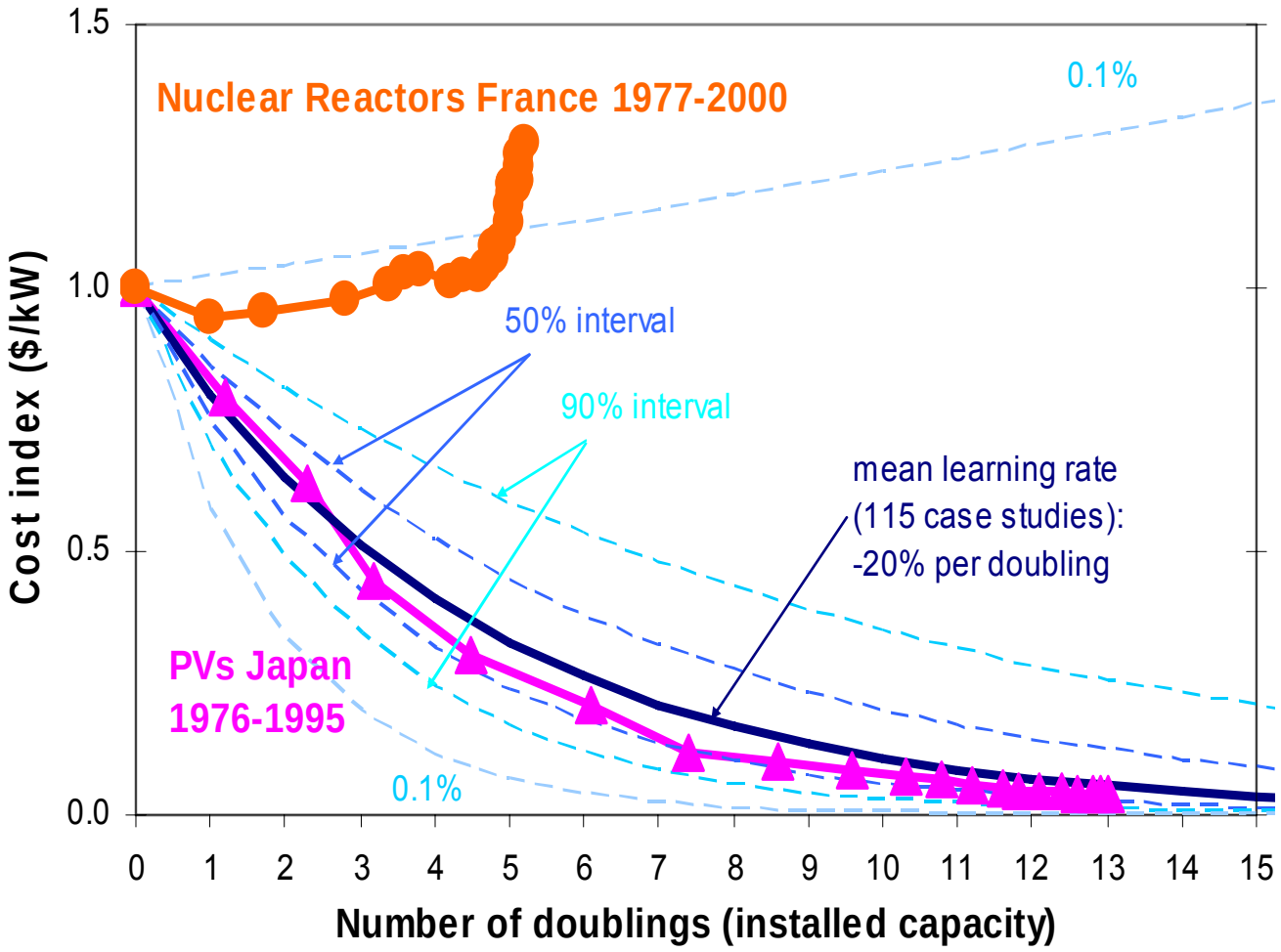


# Distribution of Learning Rates

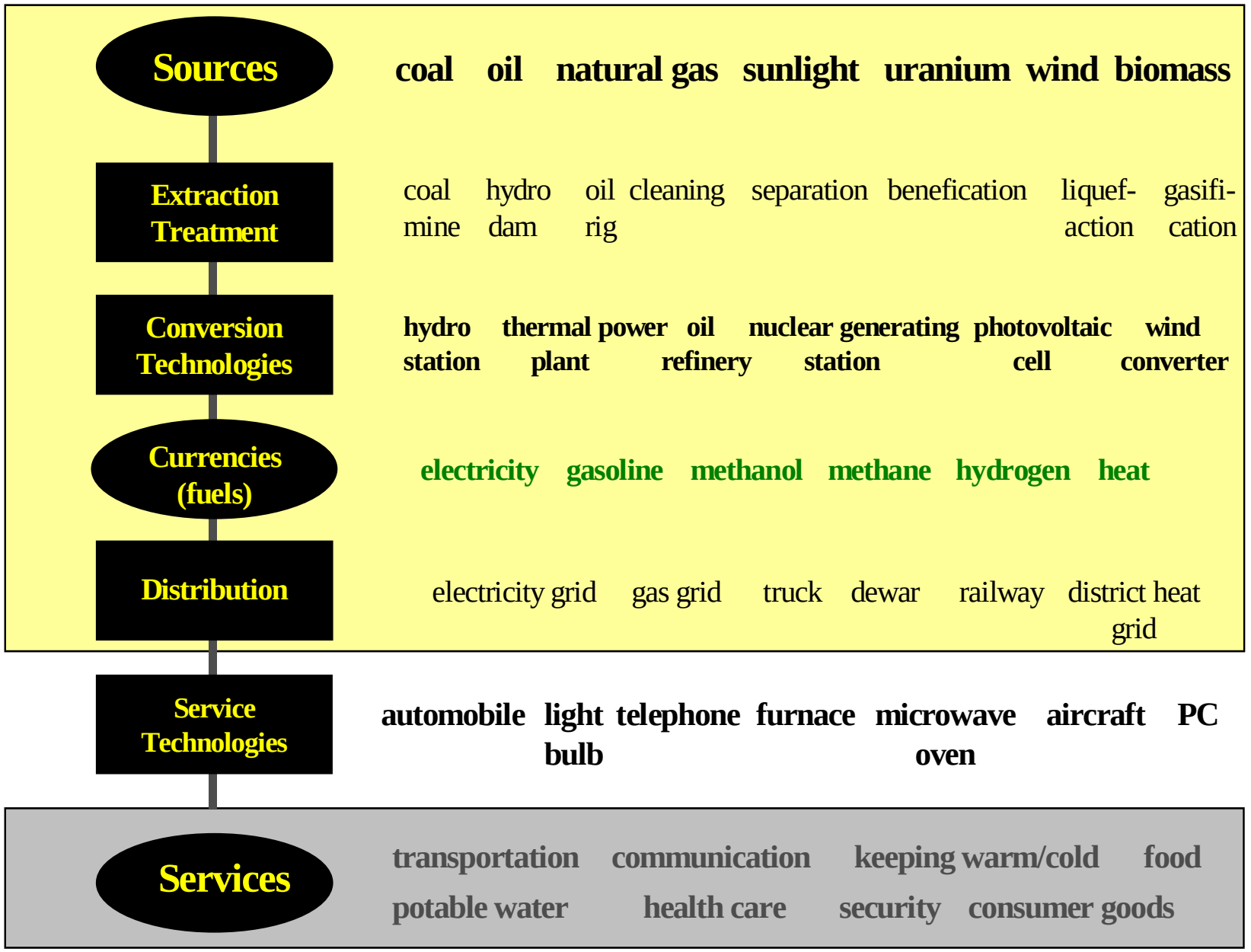
## 106 Case Studies from 22 Different Areas



# Technological Uncertainties: Learning rates (push) and market growth (pull)



# Architecture of the Energy System

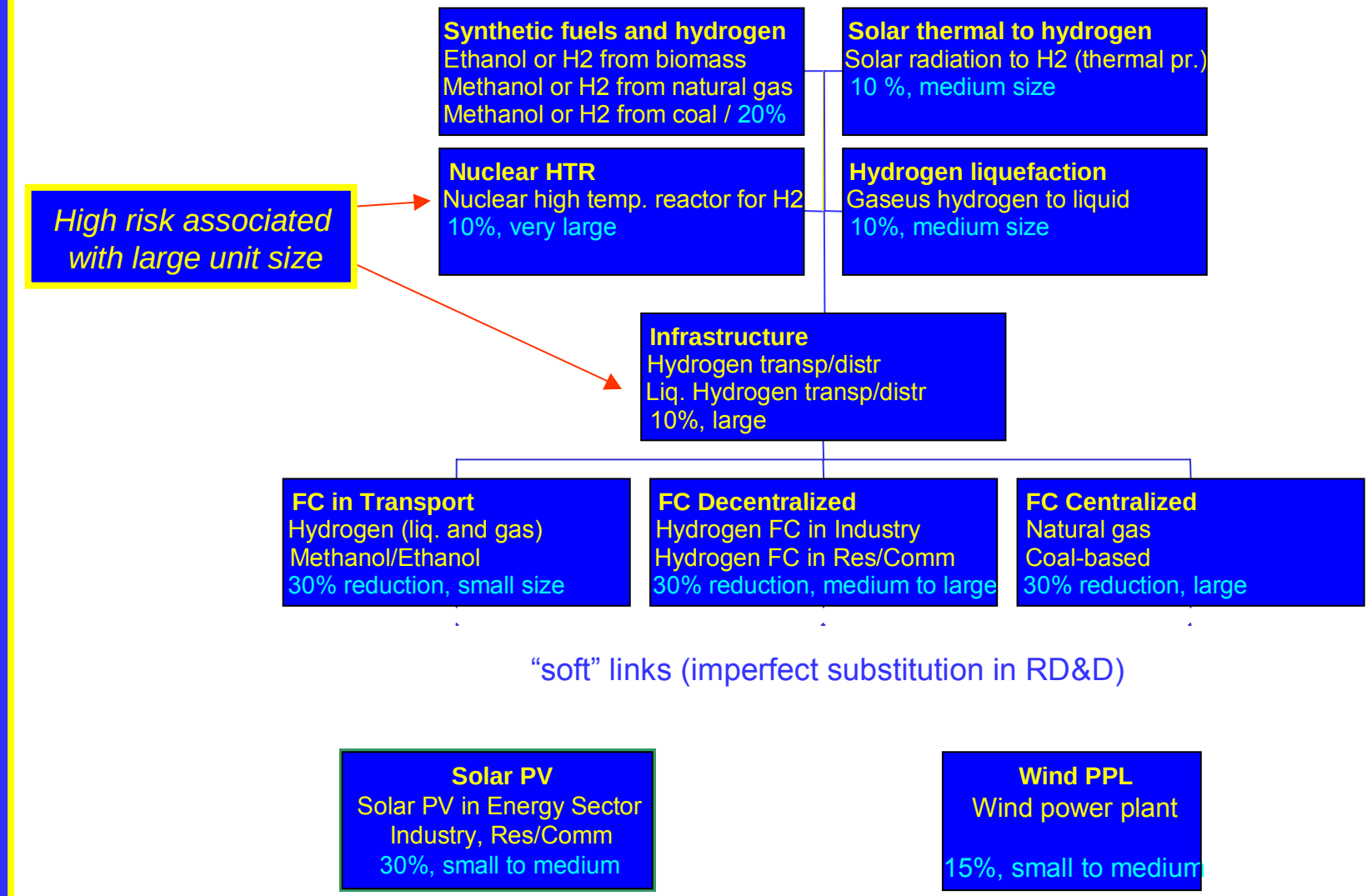



Source: WEA, 2000

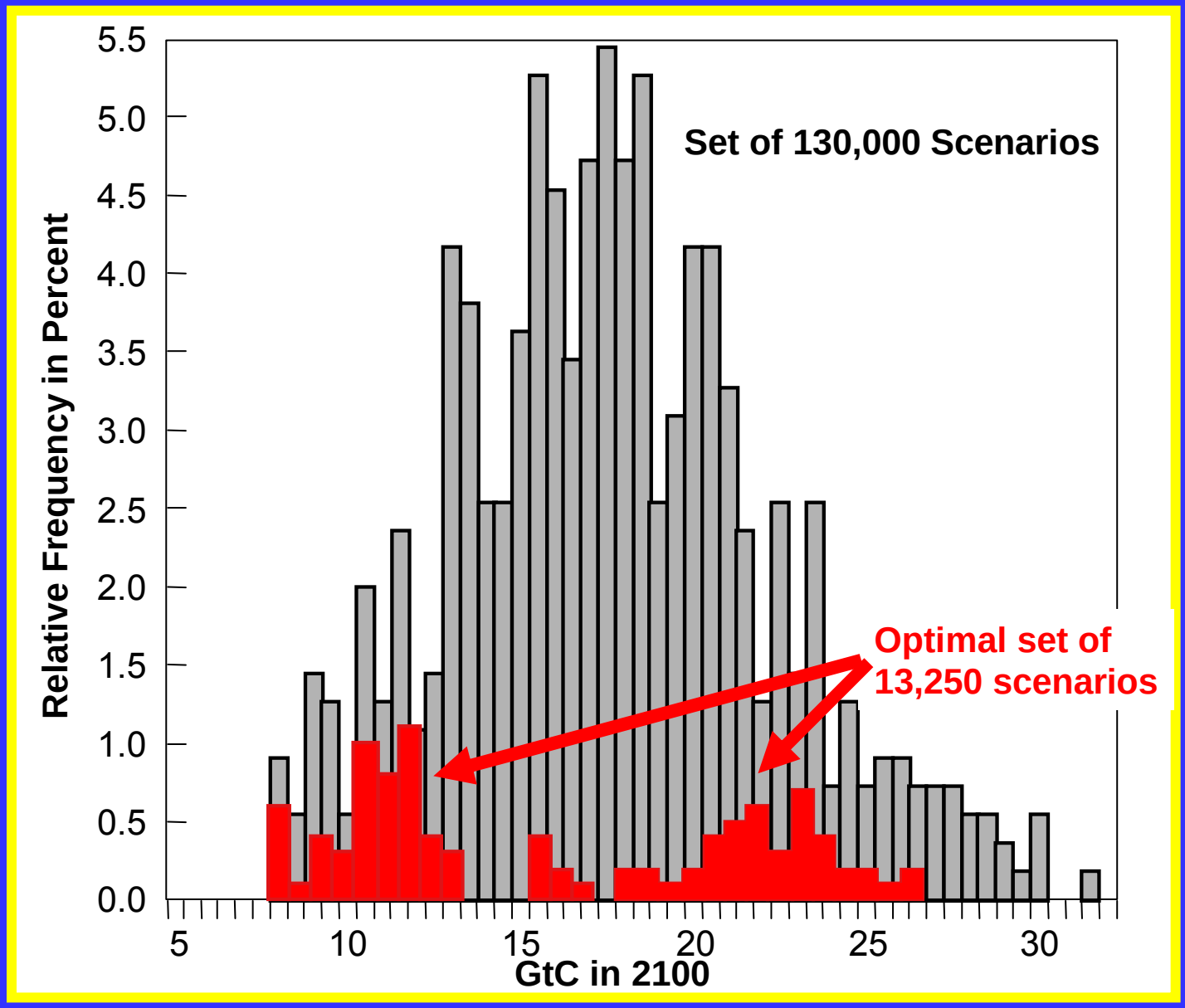
# An “Endogenous” TC Approach

The objective is to explore:

- Uncertain technology characteristics as well as learning rates
- Sequential resolution of uncertainty with one deterministic demand
- Ensembles with different systems costs, development paths and technology portfolios


Synthetic fuels and hydrogen
Ethanol or H2 from biomass
Methanol or H2 from natural gas
Methanol or H2 from coal / 20%
Solar thermal to hydrogen
Solar radiation to H2 (thermal pr.)
10 %, medium size
High risk associated with large unit size
Nuclear HTR
Nuclear high temp. reactor for H2
10%, very large
Hydrogen liquefaction
Gaseus hydrogen to liquid
10%, medium size
Infrastructure
Hydrogen transp/distr
Liq. Hydrogen transp/distr
10%, large
FC in Transport
Hydrogen (liq. and gas)
Methanol/Ethanol
30% reduction, small size
FC Decentralized
Hydrogen FC in Industry
Hydrogen FC in Res/Comm
30% reduction, medium to large
FC Centralized
Natural gas
Coal-based
30% reduction, large
"soft" links (imperfect substitution in RD&D)
Solar PV
Solar PV in Energy Sector
Industry, Res/Comm
30%, small to medium
Wind PPL
Wind power plant
15%, small to medium

# Energy Scenarios with Technological Uncertainty



# Motivation

- Deep uncertainties in the long-term: future resources, technology costs, demand, stringency of policies, …
- Scenario and sensitivity analysis are the dominant way to explore uncertainties in IAMs
- Develop a decision framework which factors in risks of uncertainties and possible response strategies

**Questions:**

- Implications of uncertainty for the technology portfolios, energy investments and emissions
- Characteristics of hedging strategies that are *robust* against uncertainties (risk management perspective)
- How much risk can be reduced and at what costs?

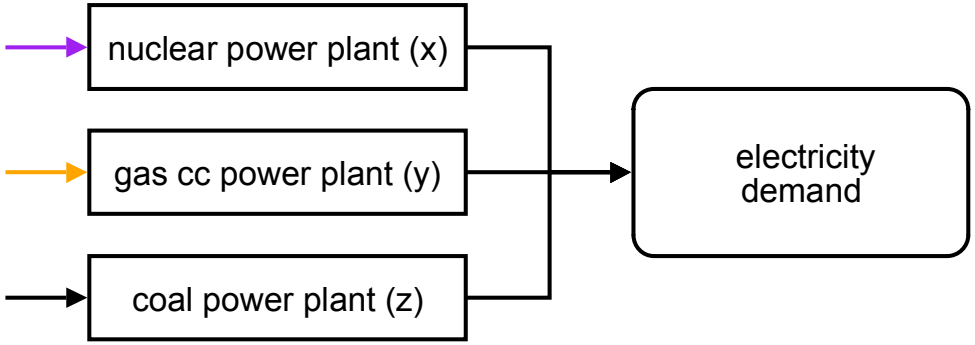
# A Simple Stochastic Example

Minimize objective function:

$$F^{\text{det}}(x, y, z) = \bar{a} \cdot x + \bar{b} \cdot y + \bar{c} \cdot z$$

s.t. (e.g. demands)

$$x + y + z \geq 1$$



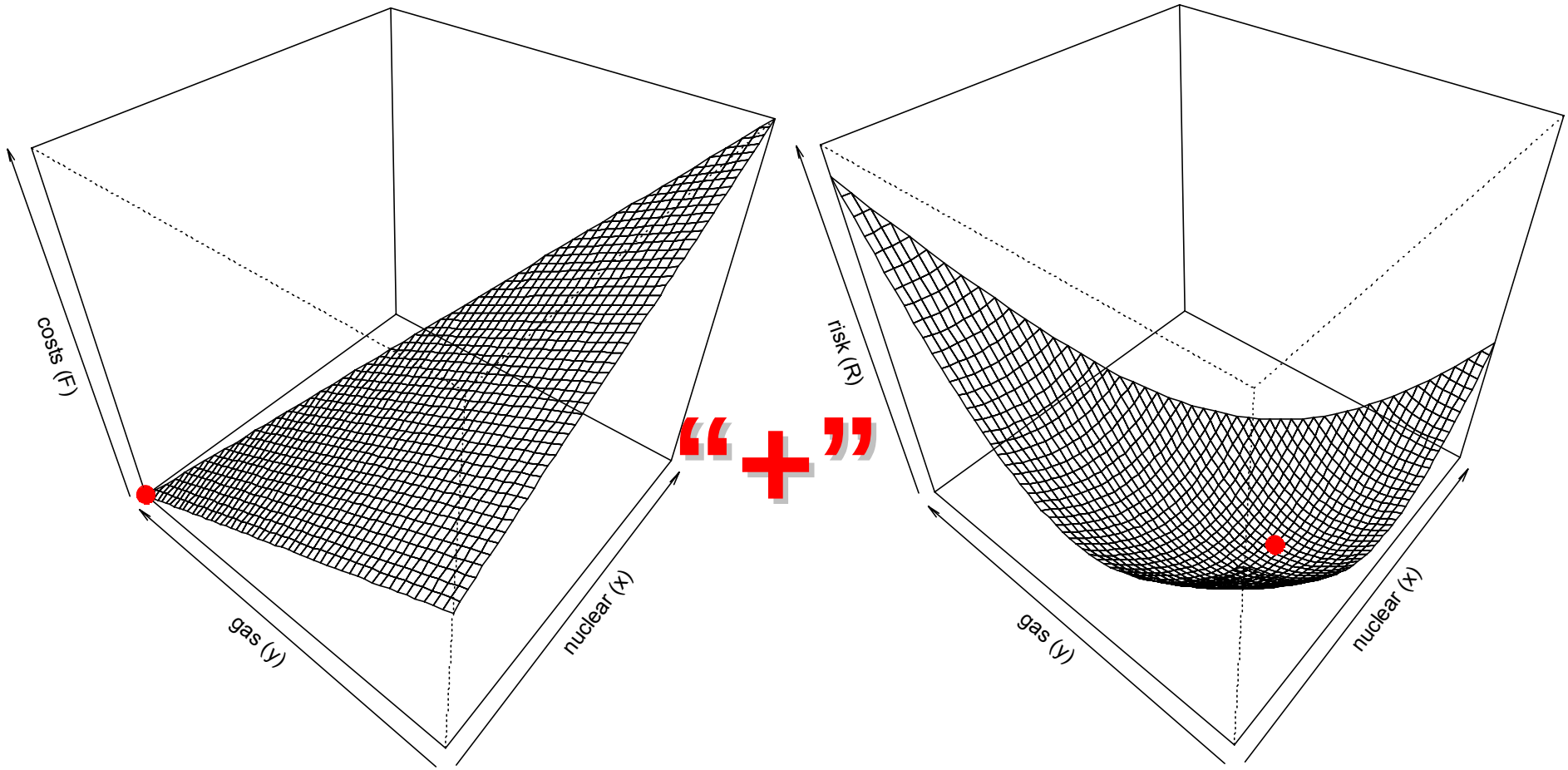

with parameters (e.g. elec generation costs)

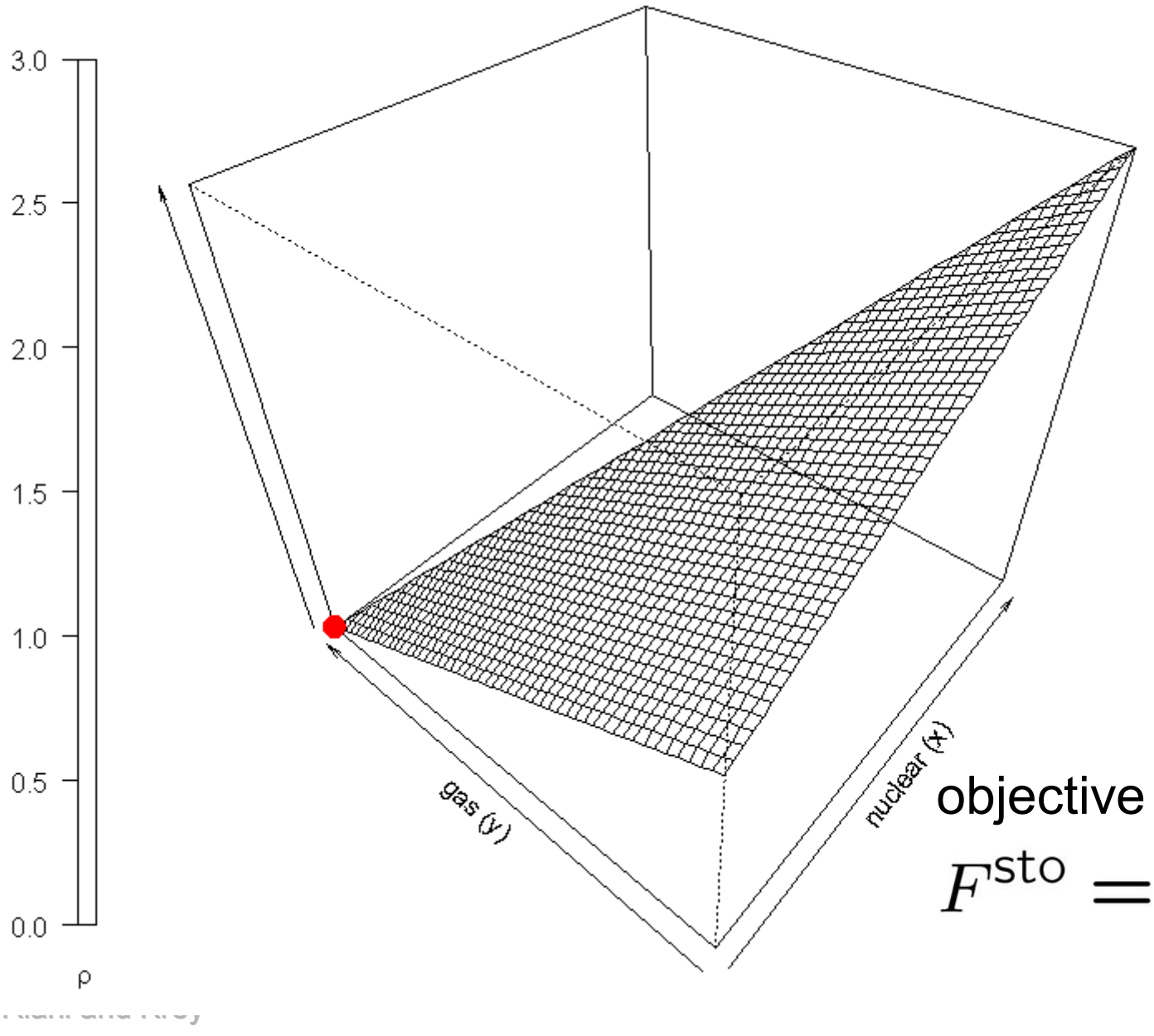
$$\bar{a} = 4.0, \quad \bar{b} = 3.5, \quad \bar{c} = 3.75$$
$$\sigma_a = 1.0, \quad \sigma_b = 1.4, \quad \sigma_c = 1.2$$

ct/kWh

# A Simple Stochastic Example

Deterministic Costs: $F^{\text{det}}(\mathbf{x})$ Risk Measure: $\bar{R}(\mathbf{x})$






objective function (z-axis):

$$F^{\text{sto}} = F^{\text{det}} + \rho \cdot \bar{R}$$

# Alternative Formulations

cost-constrained risk minimization:

$$\min \bar{R}(\mathbf{x})$$

$$\text{s.t.} \quad F^{\text{det}}(\mathbf{x}) \leq (1 + f) \cdot F^{\text{det}}(\mathbf{x}^{\star}_{\text{det}})$$

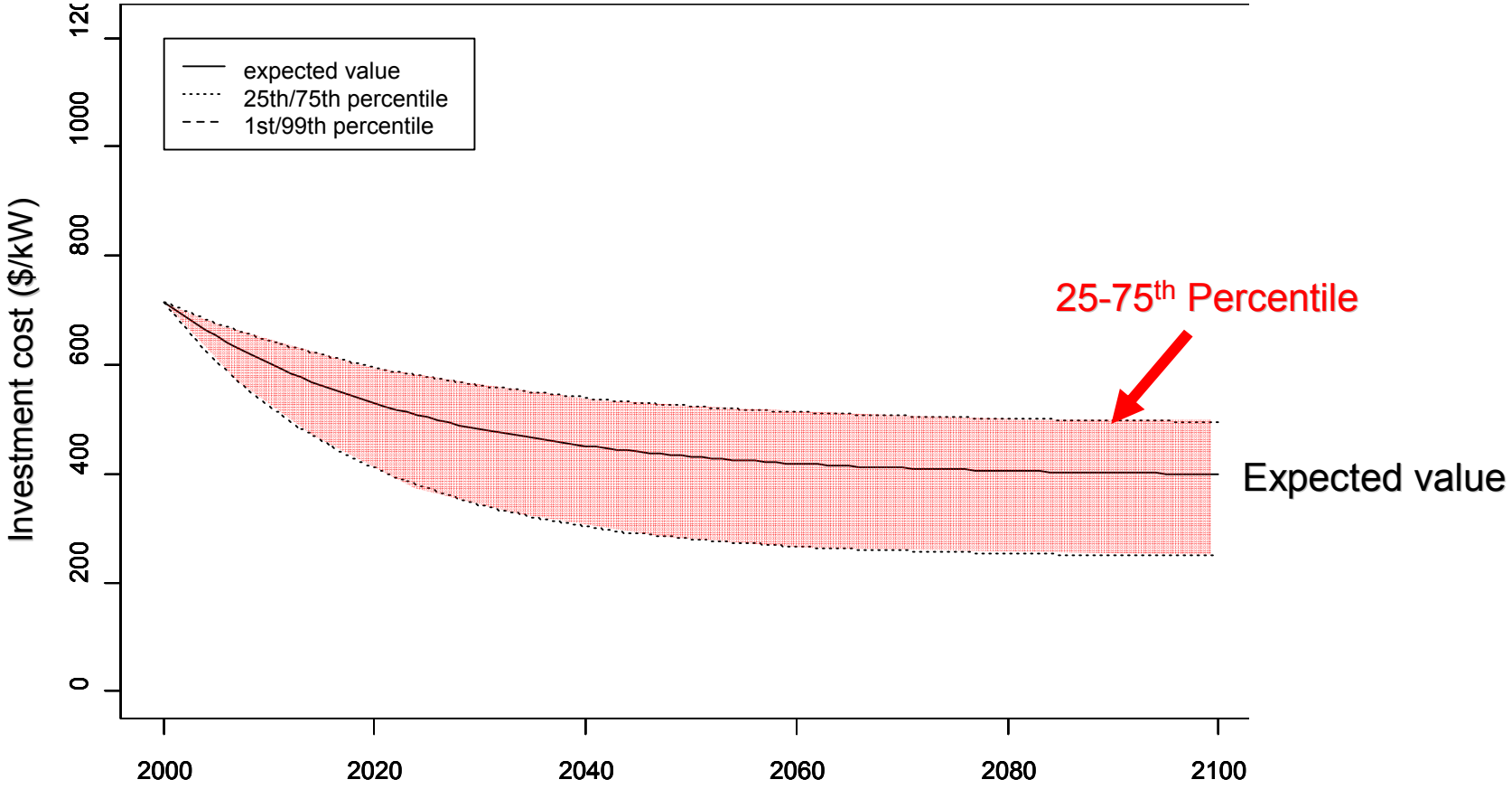
risk premium

deterministic costs

Other possibilities:

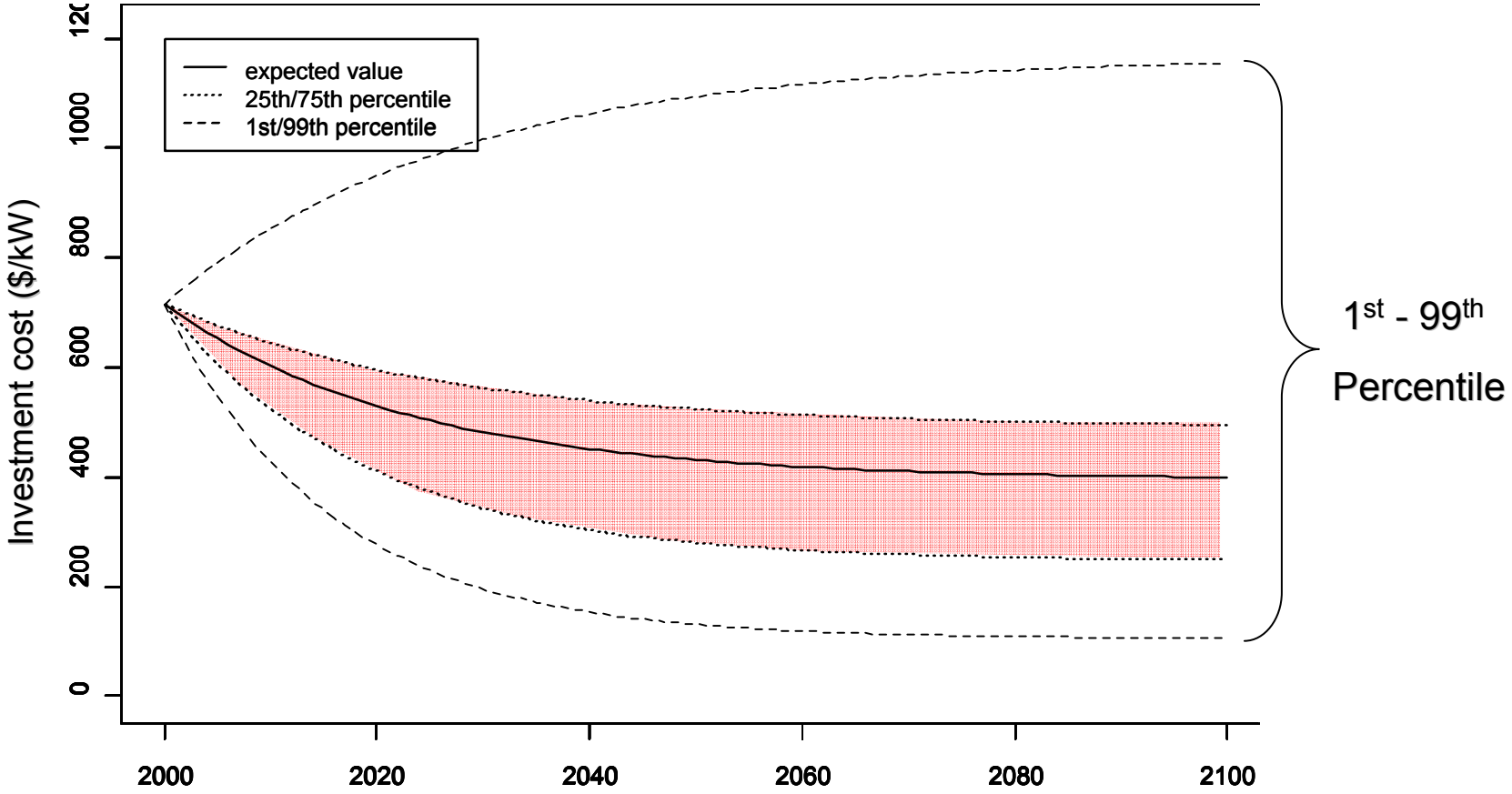
- risk-constrained cost minimization
- weighted average of costs and risk measure

# Cost Improvements over Time (NGCC)



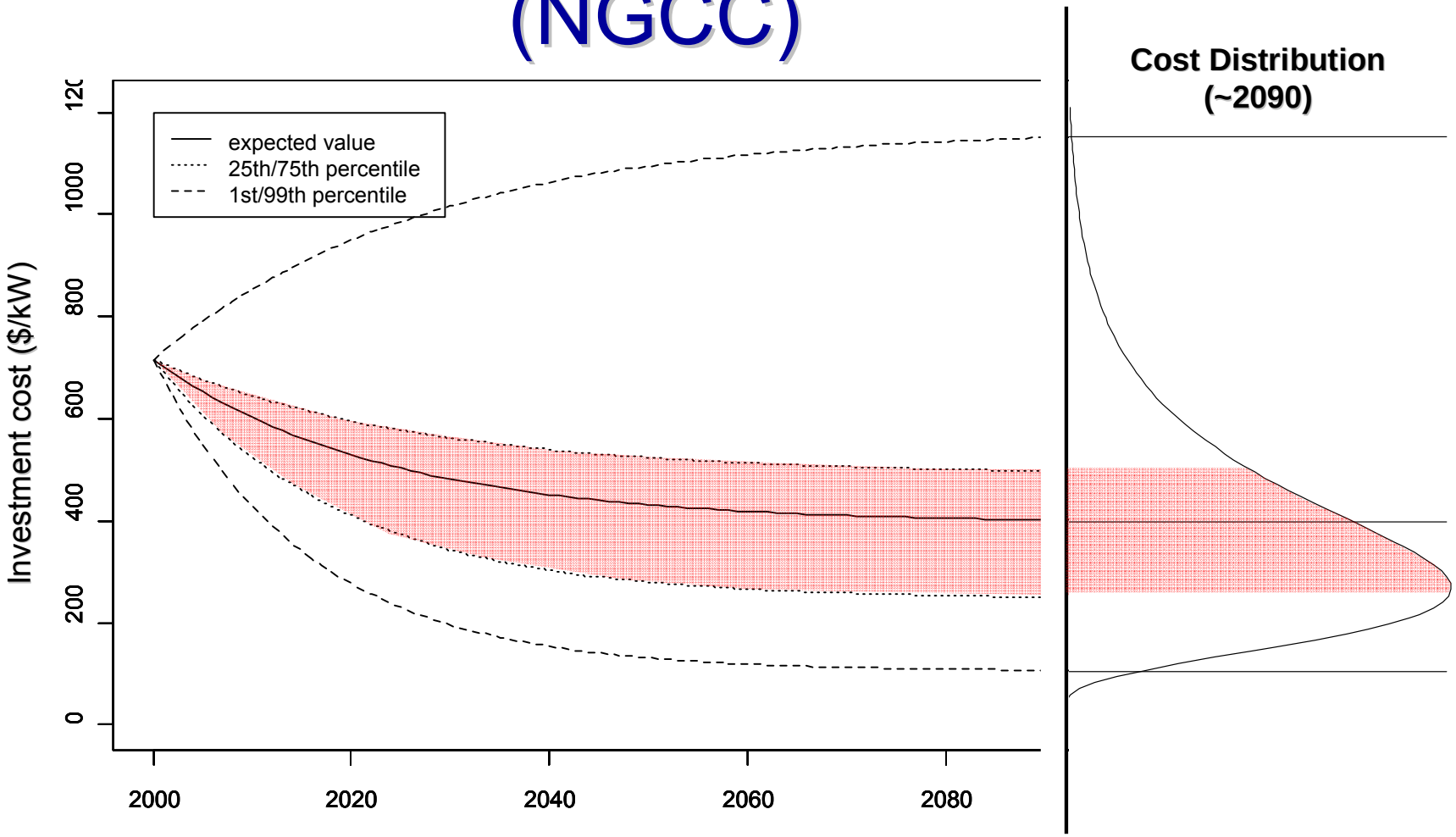

Riahi and Krey

# Cost Improvements over Time (NGCC)



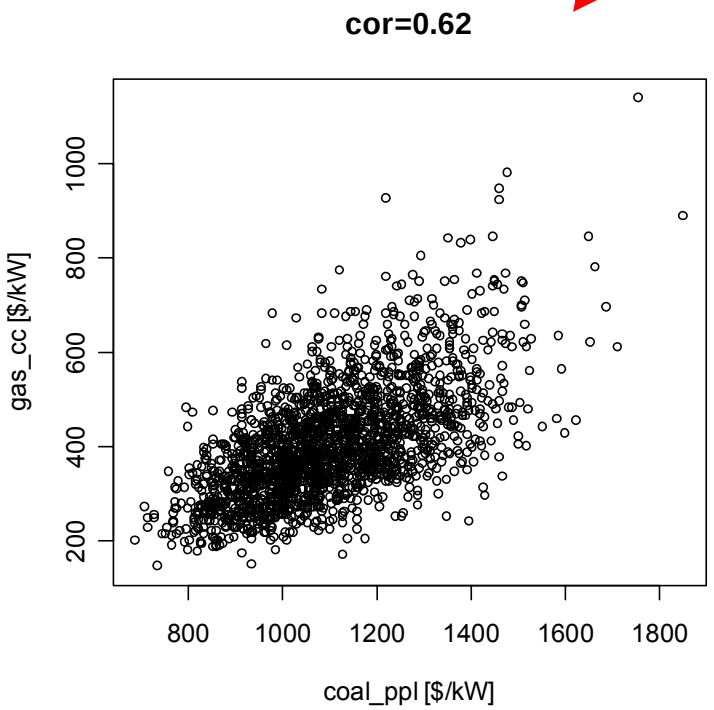

Riahi and Krey

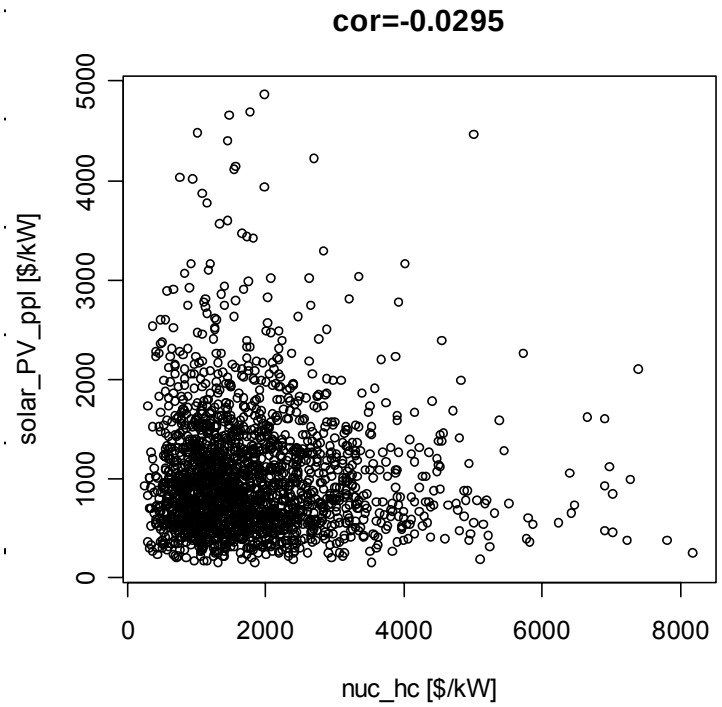
# Cost Improvements over Time (NGCC)



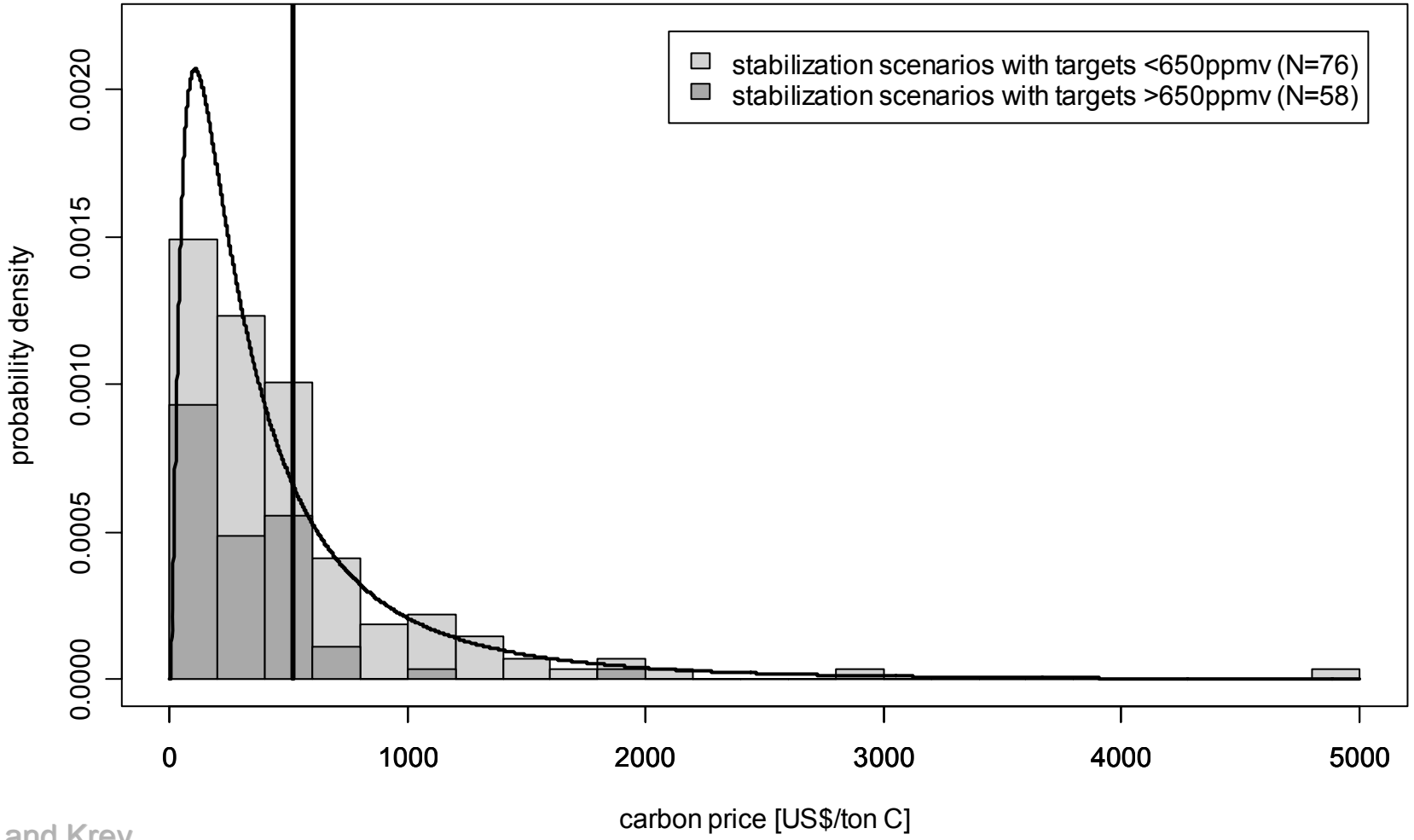
# Correlation Matrix: Electricity Generation

| | Coal | Gas | Nuclear | Biomass | Hydro | Wind | Solar |
|---|---|---|---|---|---|---|---|
| Coal | 1 | 0.63 | 0.05 | 0.57 | 0 | 0 | 0 |
| Gas | | 1 | 0.05 | 0.57 | 0 | 0 | 0 |
| | | | | | | | 0 |
| | | | | | | | 0 |
| | | | | | | | 0 |
| | | | | | | | 0 |
| | | | | | | | 0 |
| | | | | | | | 1 |



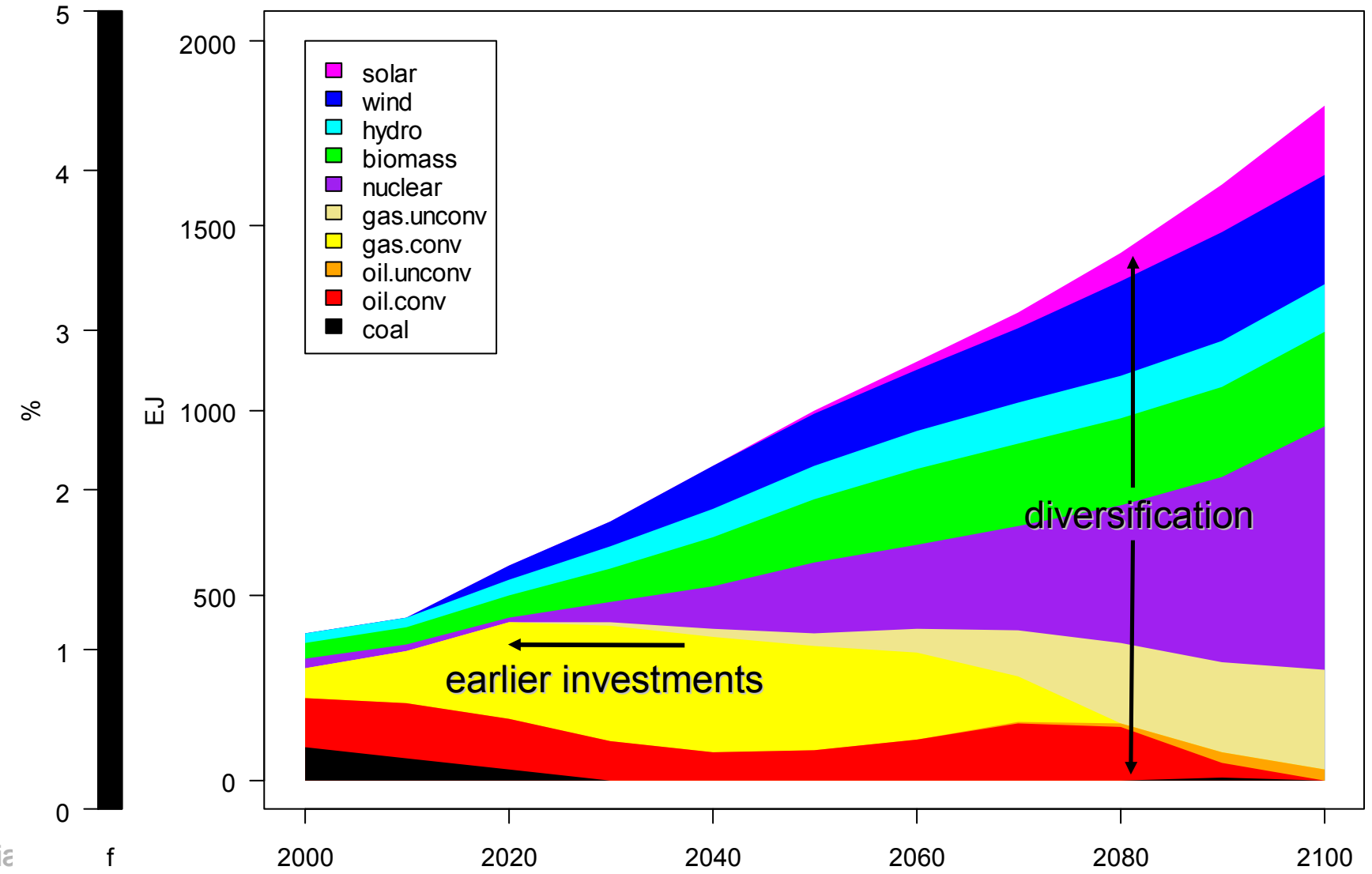



# Input Data – Carbon Price (2100)
# IPCC AR4 Scenarios

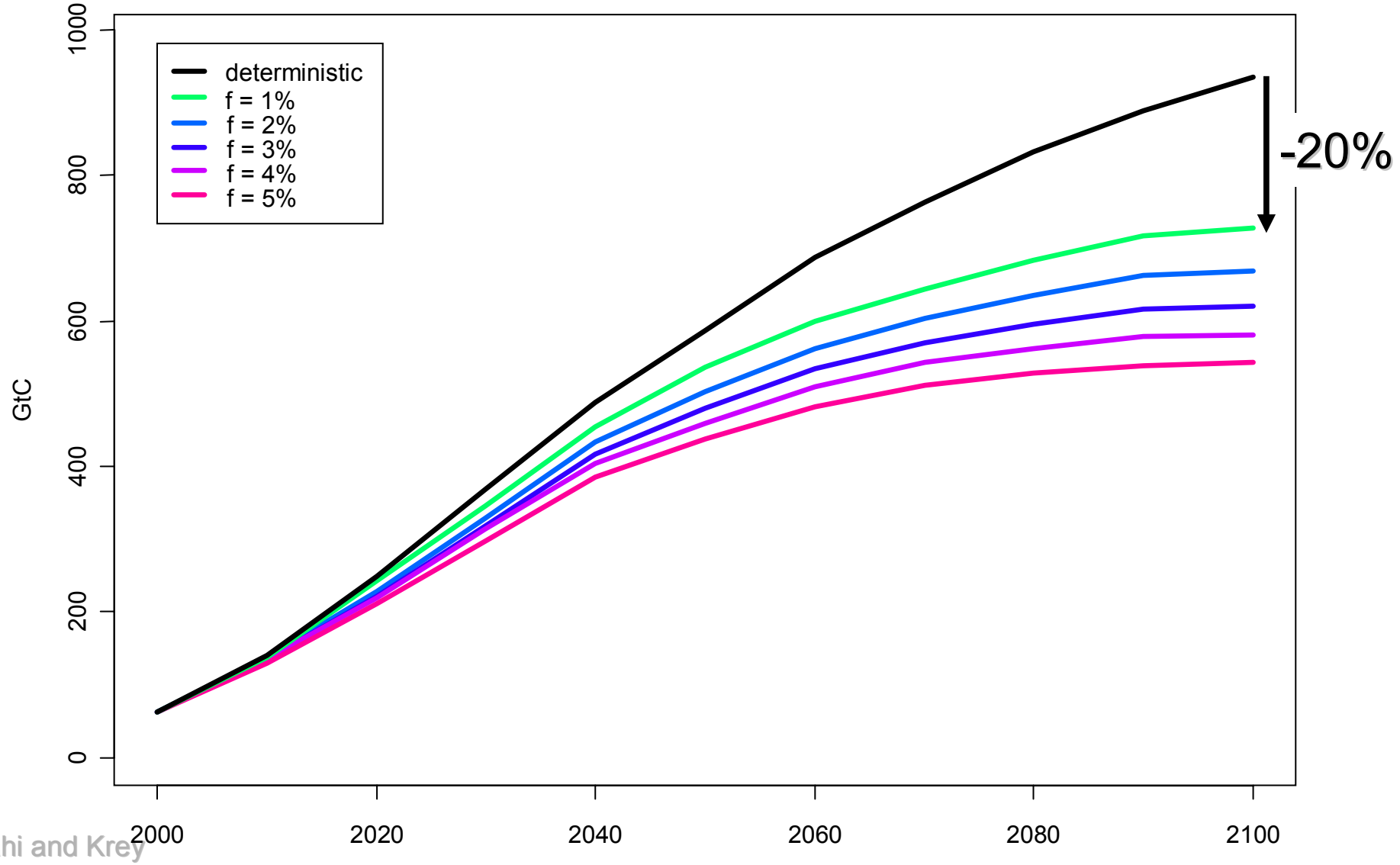



Riahi and Krey

# Total Primary Energy Supply



# Cumulative $CO_2$ Emissions



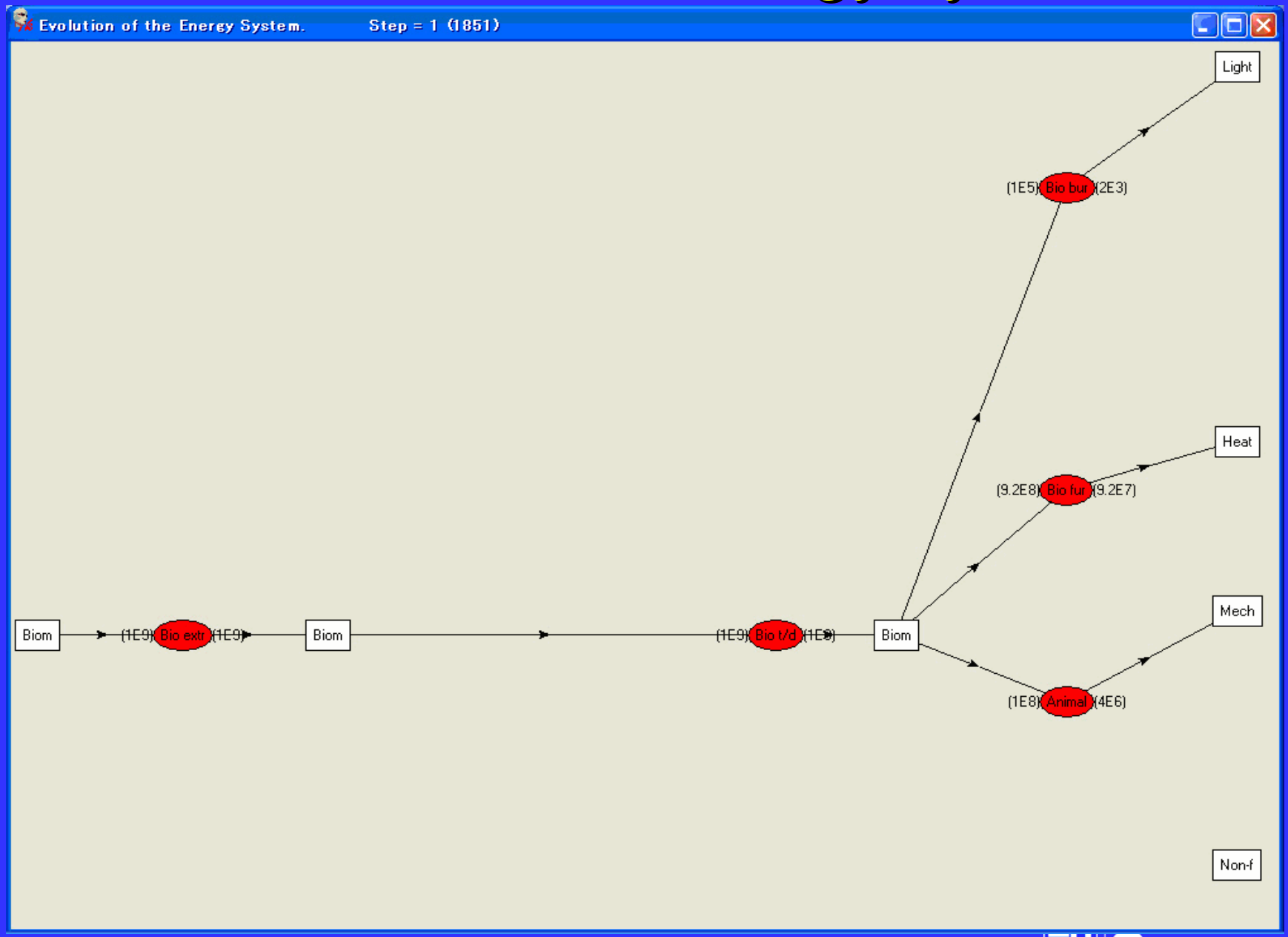

Riahi and Krey

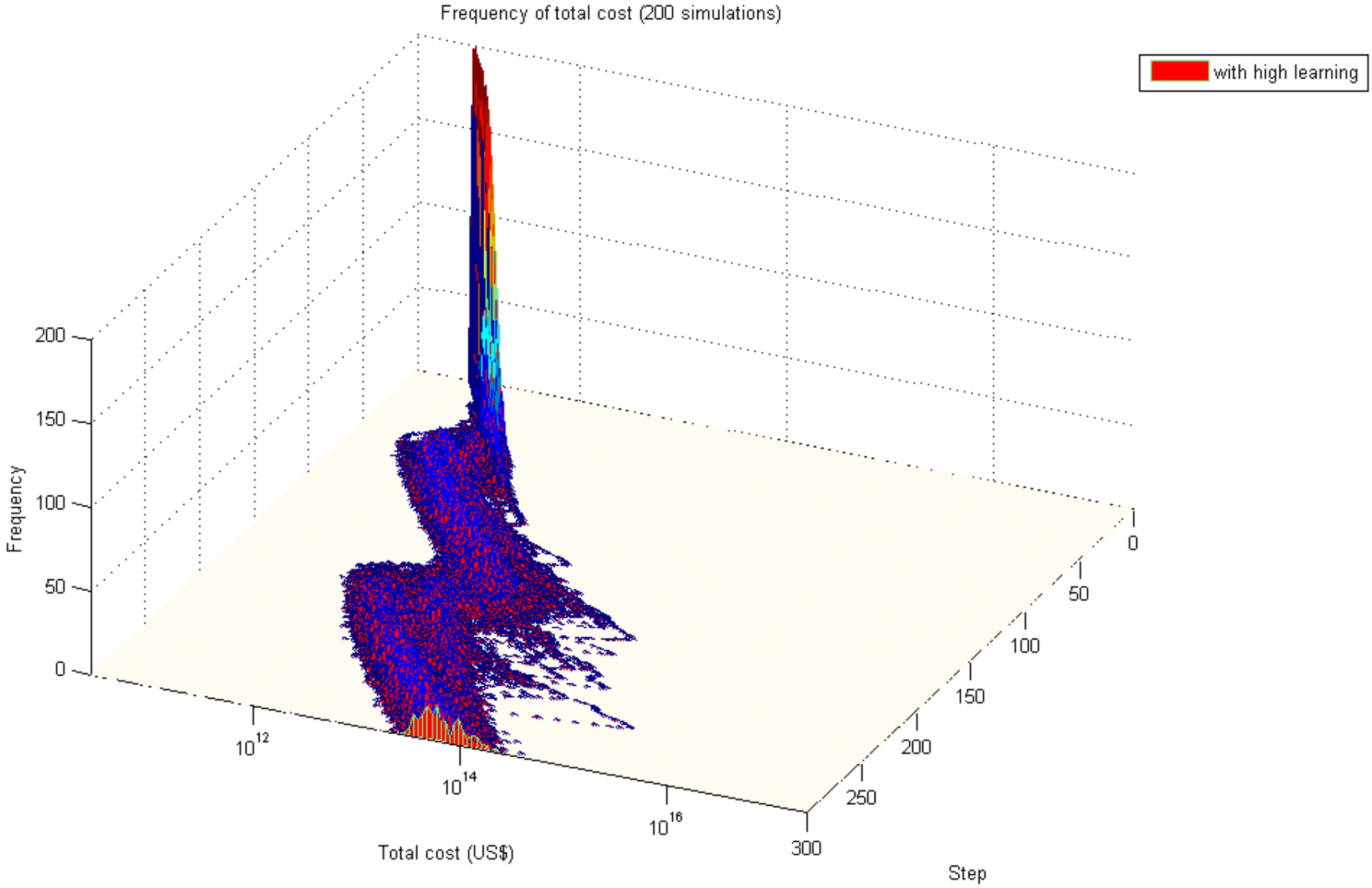
# An “Agent-Based” Approach

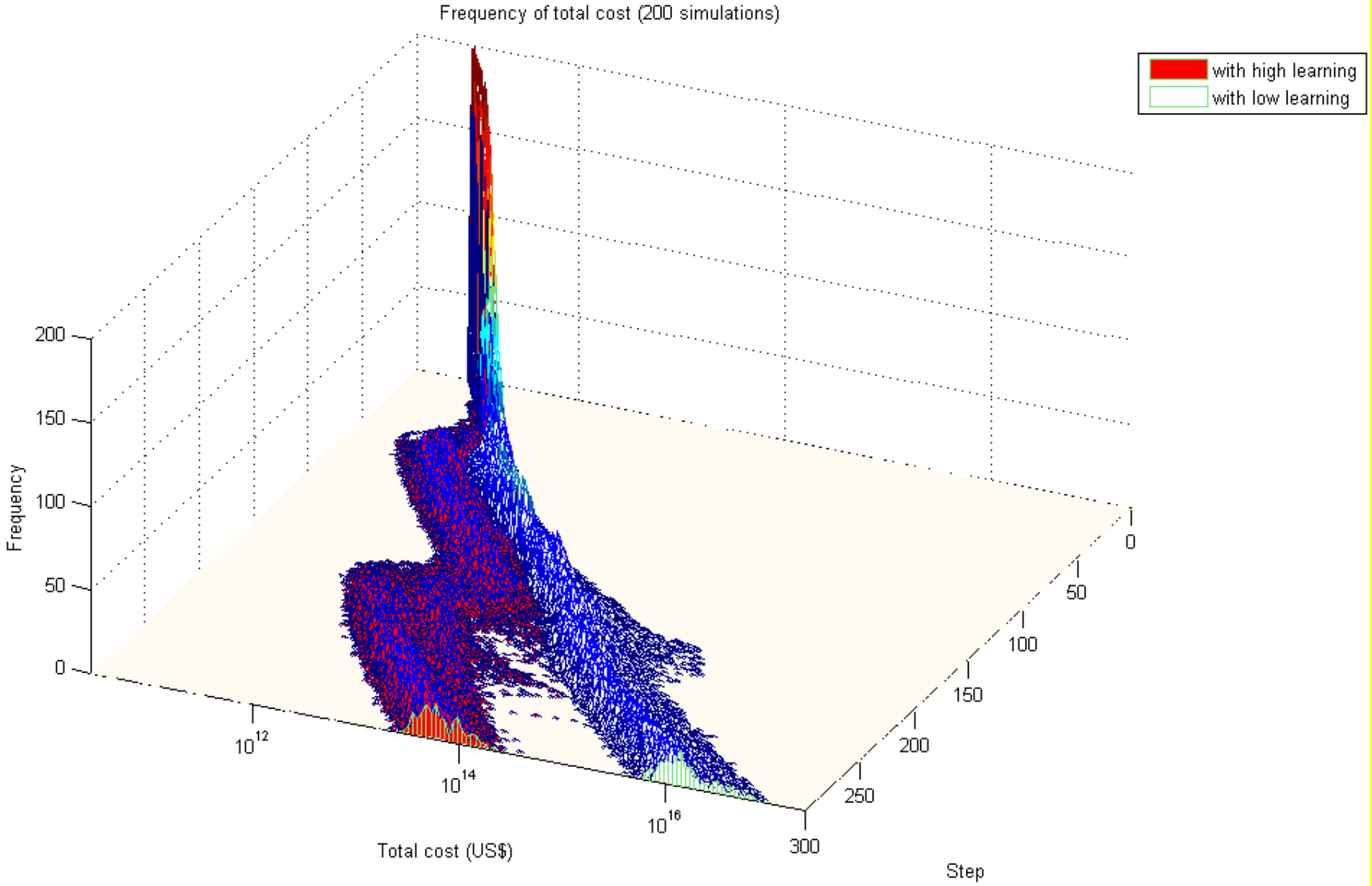
The objective is to explore:

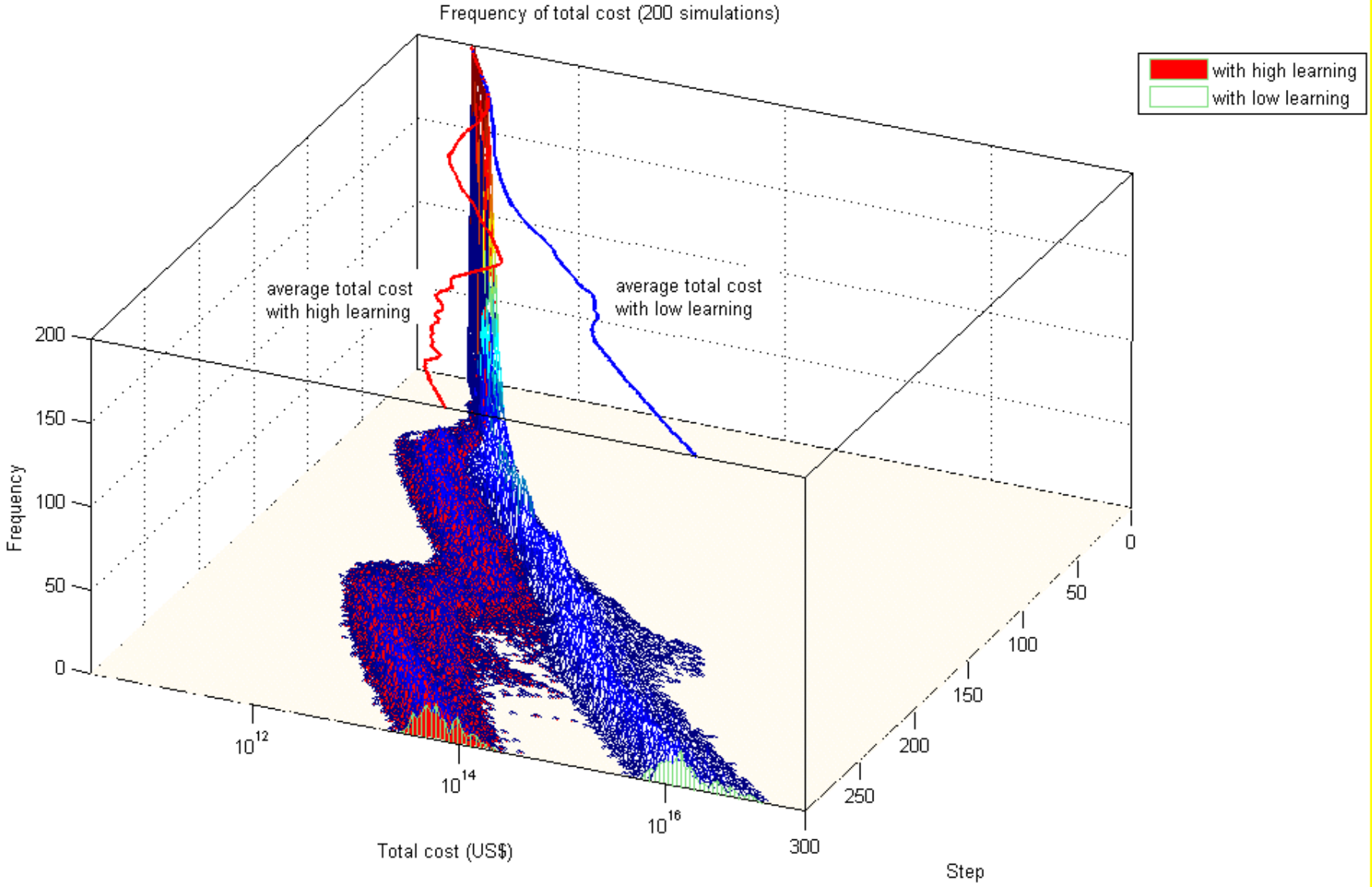
- How does technological complexity arise in energy systems?
- How an energy system will be shaped with the coming of new technologies and their combinations?
- How environment policy such as carbon taxes will influence the evolution of energy system?

# Evolution of the energy system




Frequency of total cost (200 simulations)
with high learning
Frequency
200
150
100
50
0
$10^{12}$
$10^{14}$
$10^{16}$
Total cost (US$)
0
50
100
150
200
250
300
Step


Frequency of total cost (200 simulations)
with high learning
with low learning
Frequency
200
150
100
50
0
$10^{12}$
$10^{14}$
$10^{16}$
Total cost (US$)
0
50
100
150
200
250
300
Step


Frequency of total cost (200 simulations)
with high learning
with low learning
average total cost
with high learning
average total cost
with low learning
Frequency
200
150
100
50
0
$10^{12}$
$10^{14}$
$10^{16}$
Total cost (US$)
300
250
200
150
100
50
0
Step

# Technological Change: Dynamic, Cumulative, Systemic and Uncertain

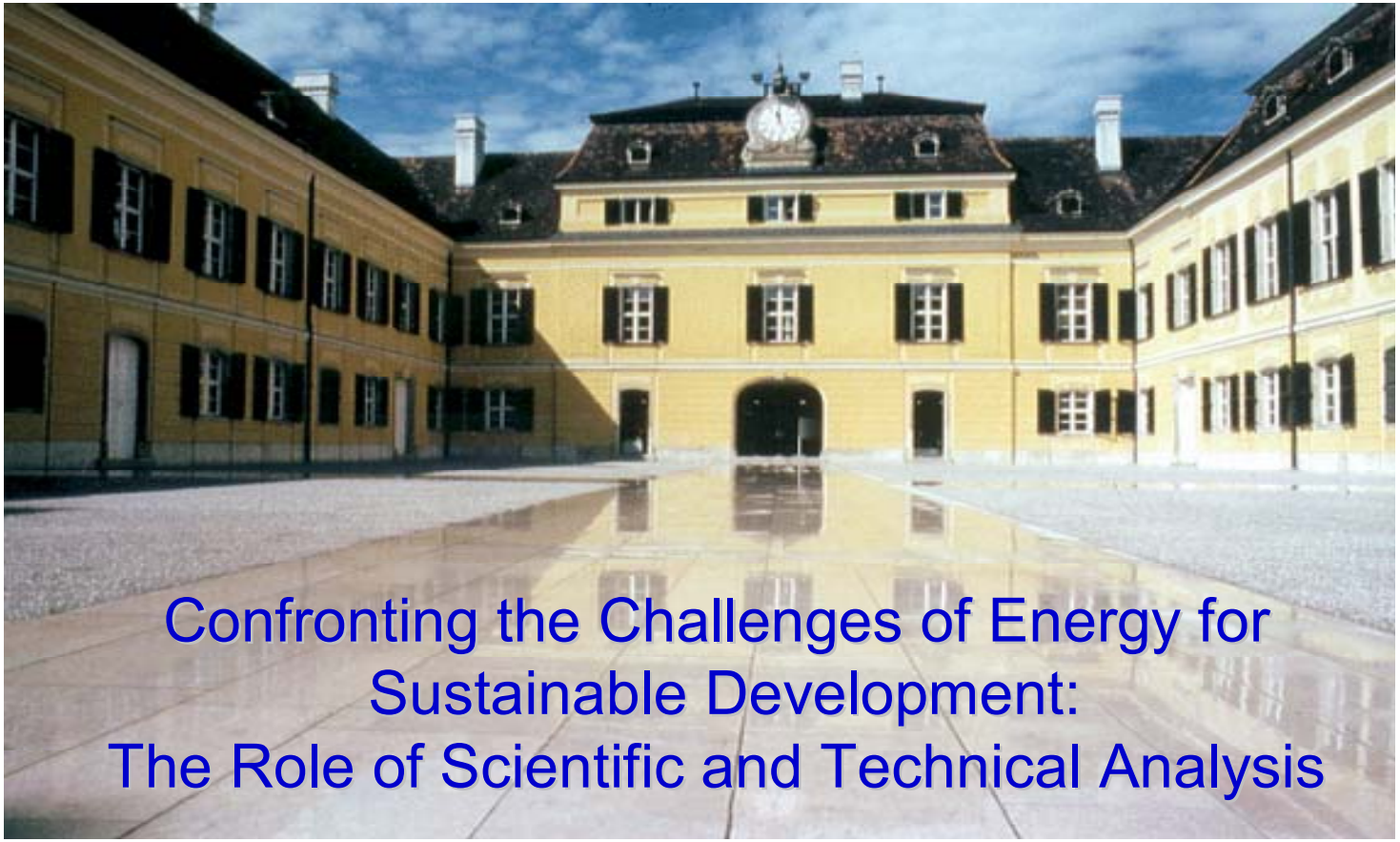
- Study the failures; we basically work with a history of successes (people loose money on innovations); infrastructures
- Heterogeneity of agents, policies and local conditions; spatial data sets are necessary; rural-urban; “let 1k flowers bloom”
- “Big hits” from the tails of the distributions (in systems context); need to compare technology assumptions and develop frequency distributions both for successes and failures, particularly end use
- Comparison of assumptions; how to build future systems in our models and account of inherent deep uncertainty through distribution functions or behavior of agents

http://www.iiasa.ac.at/Research/ENE/index.html

http://www.iiasa.ac.at/Research/TNT/index.html

http://www.eeg.tuwien.ac.at/

naki@iiasa.ac.at



# Confronting the Challenges of Energy for Sustainable Development: The Role of Scientific and Technical Analysis

**IIASA**

International Institute for Applied Systems Analysis

presents

**www.GlobalEnergyAssessment.org**