Energie, Entropie und Wirtschaftswachstum
(Energy, Entropy, and Economic Growth)

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Program

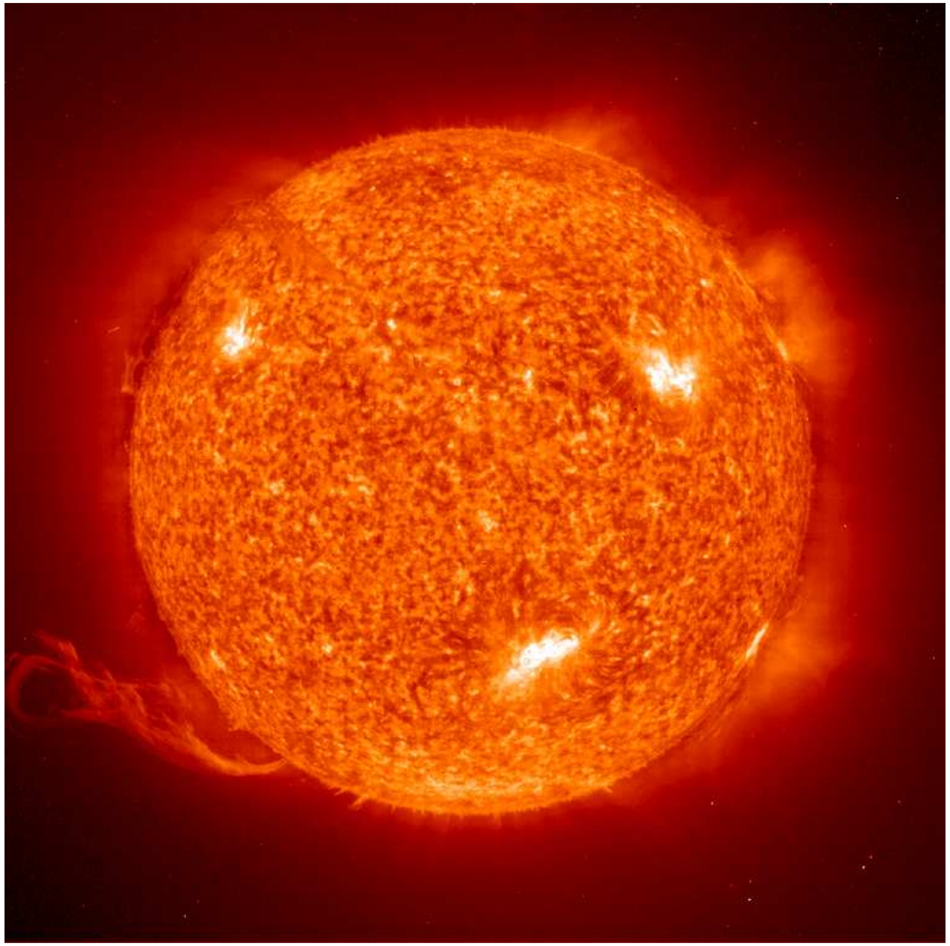
"Energy generation, distribution and use is critical to modern economies, both as an input to industrial production and as an important element of consumer spending. At the same time, current patterns of energy generation and use contribute significantly to environmental problems, such as climate change and air pollution."

OECD, Taxing Energy Use: A Graphical Analysis. OECD Publishing, 2013

1. Energy and entropy
   - The First and the Second Law of Thermodynamics
   - Global energy consumption and CO_2 emissions
   - "The Limits to Growth" and oil-price shocks: When physics began to matter in economics
2. Economic growth
   - Economists' views on energy
   - The capital, labor, energy, creativity (KLEC) model
   - Germany, Japan, USA: Growth and output elasticities
   - Profit (and welfare) optimization subject to constraints
3. Summary and Conclusion

Details in: "The Second Law of Economics: Energy, Entropy, and the Origins of Wealth". Springer, New York . . . 2011

Energy: The capacity to cause changes

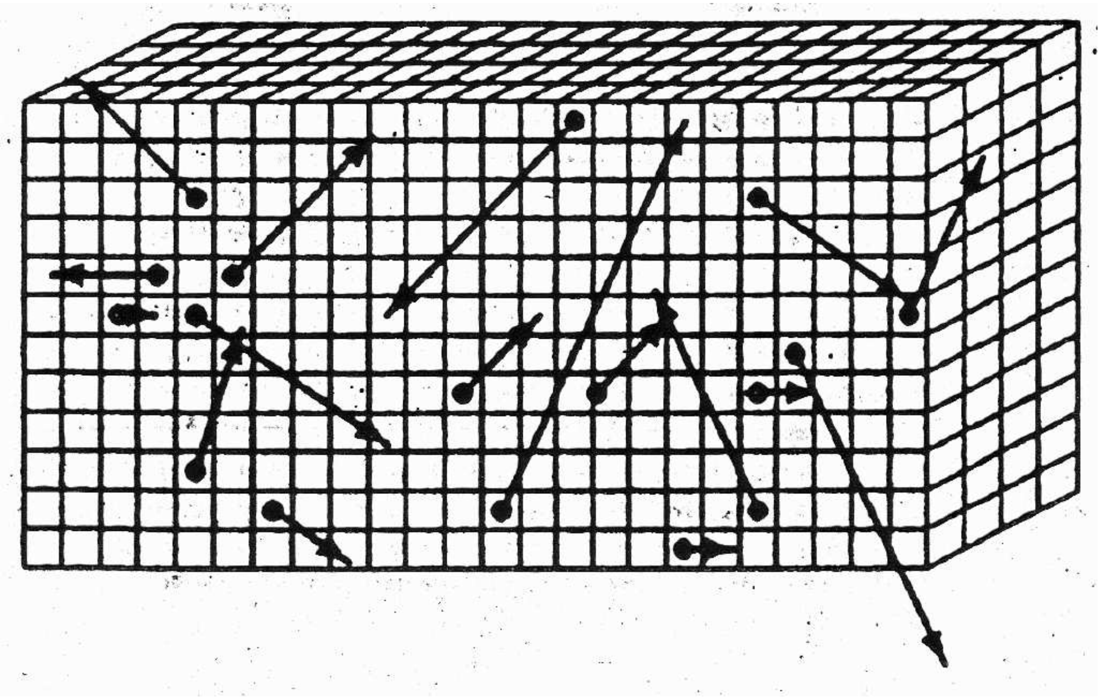


Per second, the Sun converts $600 \cdot 10^6$ tons of hydrogen into helium. Mass difference: $\Delta m = 4.2 \cdot 10^6$ tons. Solar photoluminosity $L = \Delta mc^2/s = 3.845 \cdot 10^{26}$ W. Earth absorbs $1.2 \cdot 10^{17}W \approx 10^4$ present world energy consumption.

Entropy: The physical measure of disorder

A monster 's there that always shows,
the more you work the more it grows.

Entropy $S = k_B \ln \Omega$



One Many-body state of an ideal gas.

Postulate of equal *a priori* probabilities: An isolated system in equilibrium can be found with equal probability in any one of its accessible states Ω.

1971, Georgescu-Roegen: “The Entropy Law and the Economic Process”

1st and 2nd Law of Thermodynamics

- **Nothing happens in the world**
  without energy conversion and entropy production.
  First and Second Law of Thermodynamics

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  Exergy: valuable part of energy, convertible into useful work.
  Anergy: useless; e.g. heat dumped into the environment.

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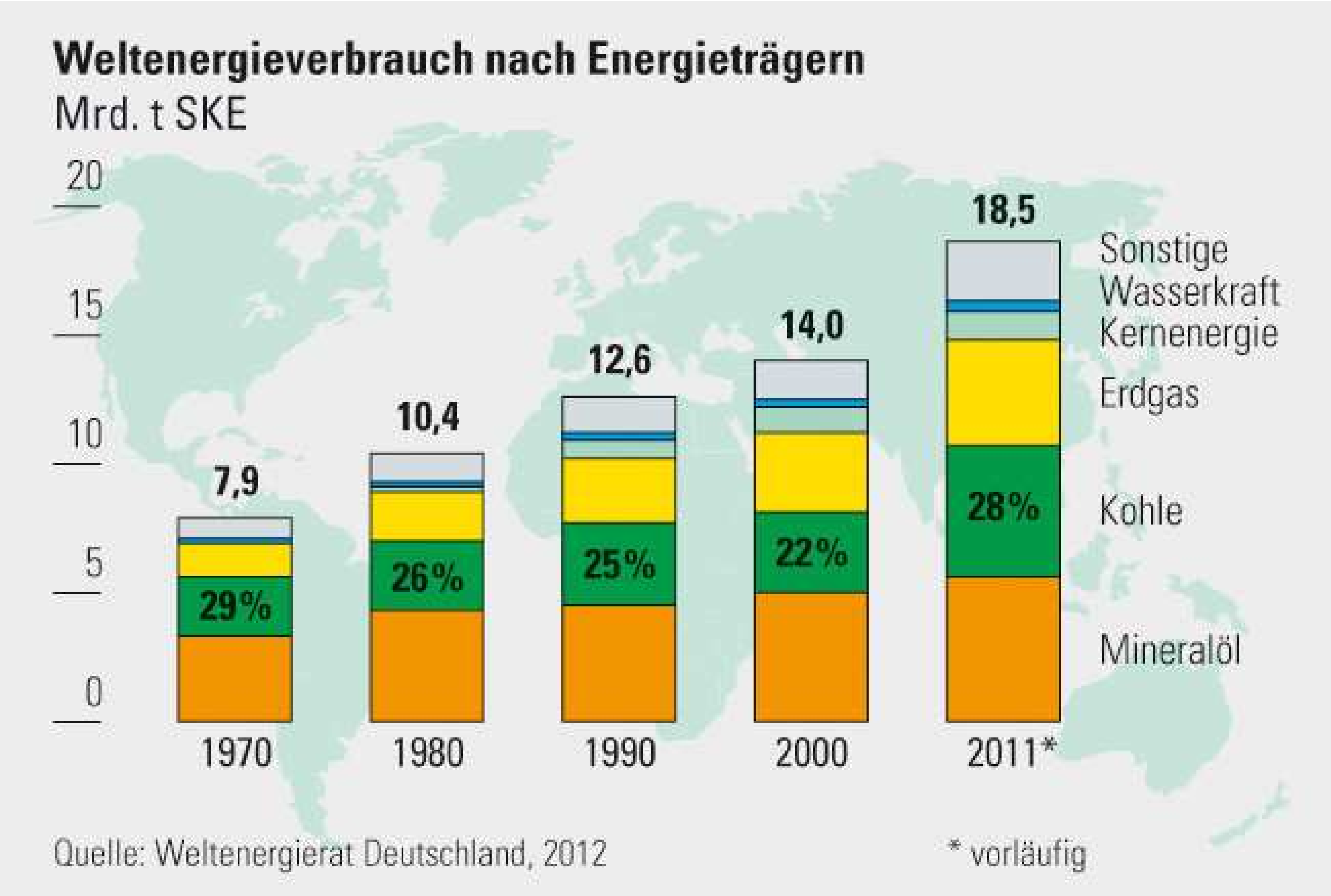
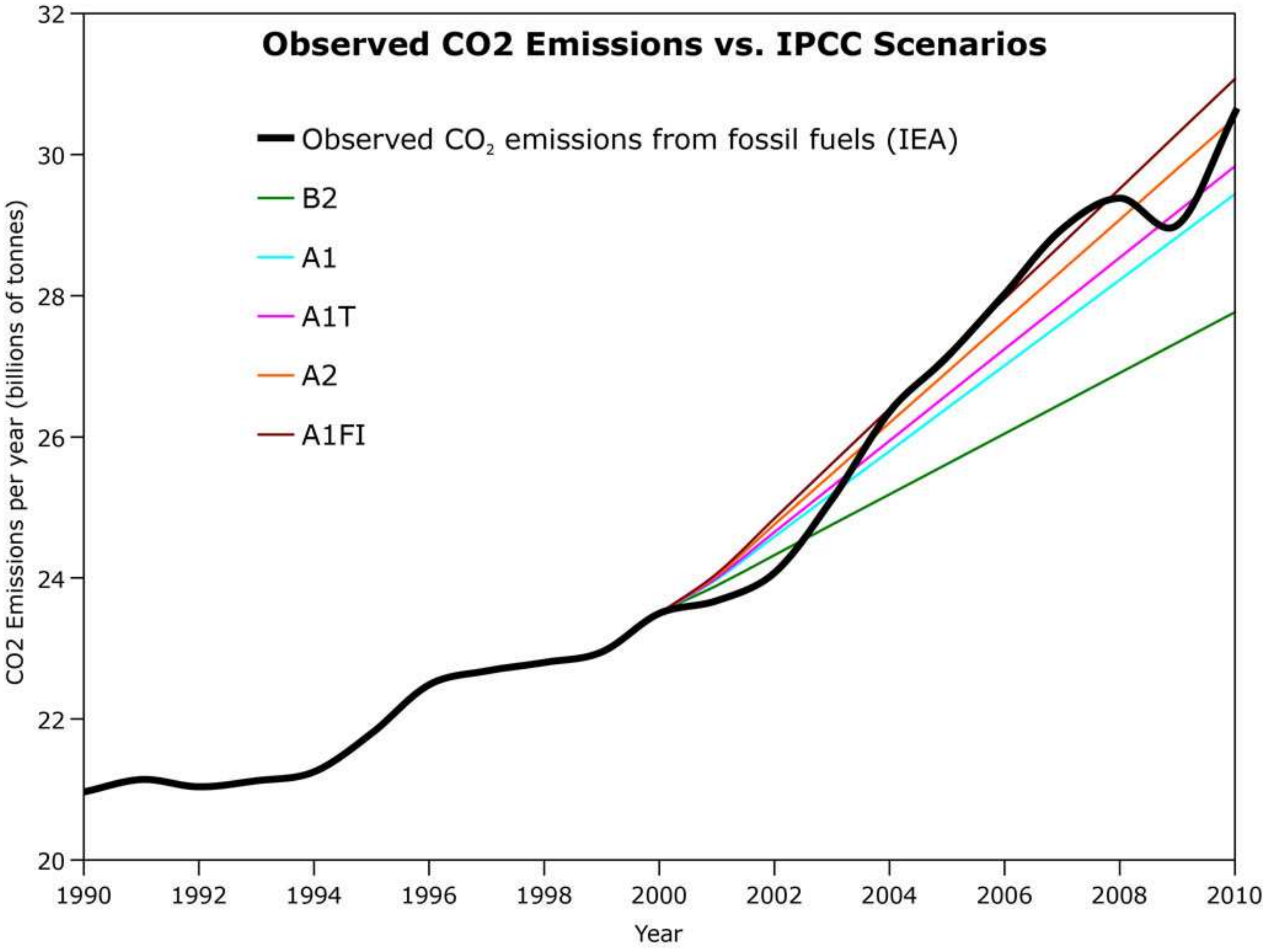
- Second Law: unavoidable entropy production
  1) destroys exergy, enhances useless anergy $\longrightarrow$ limits to improvements of energy efficiency!
  2) results in polluting emissions of particles and heat:
  entropy production density in a non-equilibrium system of N different sorts of particles k:
  $\sigma_{S,dis}(\vec{r},t) = \sum_{k=1}^{N} \vec{j}_k[-\vec{\nabla}(\mu_k/T) + \vec{f}_k/T] + \vec{j}_Q \vec{\nabla}(1/T) > 0$.
  $\vec{j}_k$ = particle current density, $\vec{j}_Q$ = heat current density,
  ($\vec{\nabla}$: gradient, T = temperature, μ_k= chemical potentials,
  $\vec{f}_k$ = external forces.)
  Air pollution (China!), climate change

Growth of global energy consumption



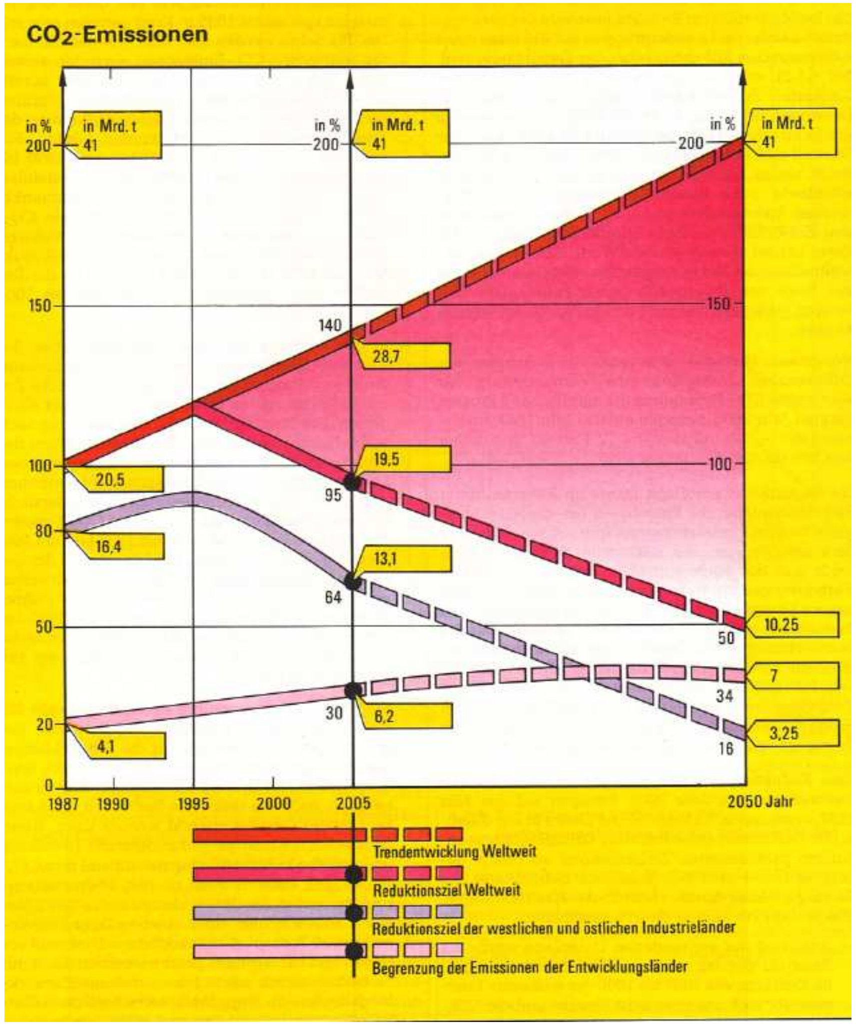
18,5 Mrd. t SKE/ Jahr = 18.5 10^9 tCE/year = 1.72 10^{13}W

Fossil-fuel CO_2 emissions 1990–2010



Source: http://www.skepticalscience.com/iea-co2-emissions-update-2010.html

Emission mitigation

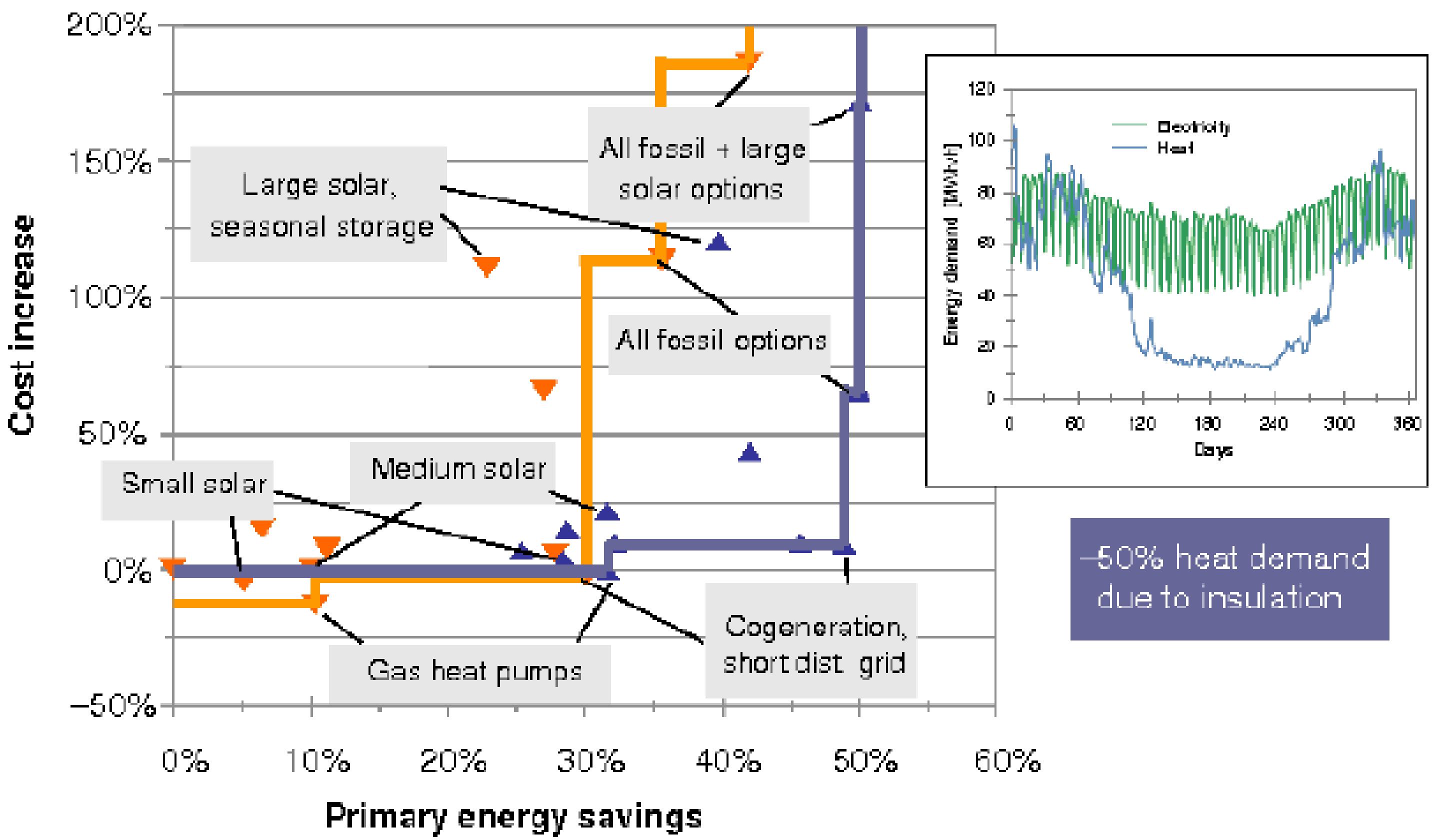


Proposal of the “Study Commission on Preventives Measures to Protect the Earth’s Atmosphere” of the German Parliament to reduce the annual CO_2 emissions, so that the concentration of CO_2 will not exceed 560 ppm (which is twice the pre-industrial concentration) and global temperature increase will not exceed 2 centigrades.

Scenarios for exergy optimization

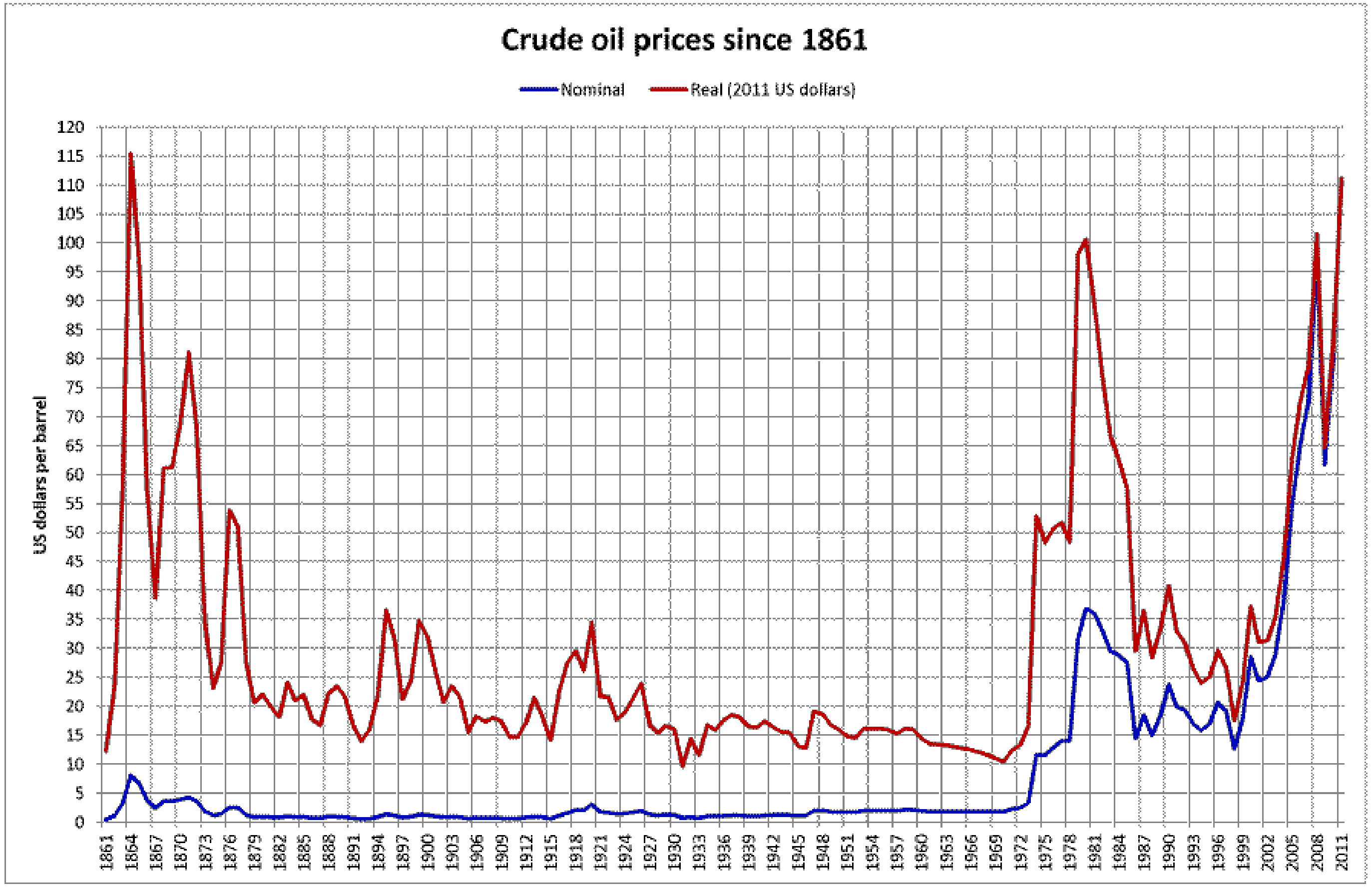
deeco

CHP, demand reduction, and renewable energies



How the energy demand of “Würzburg” could be satisfied optimally.

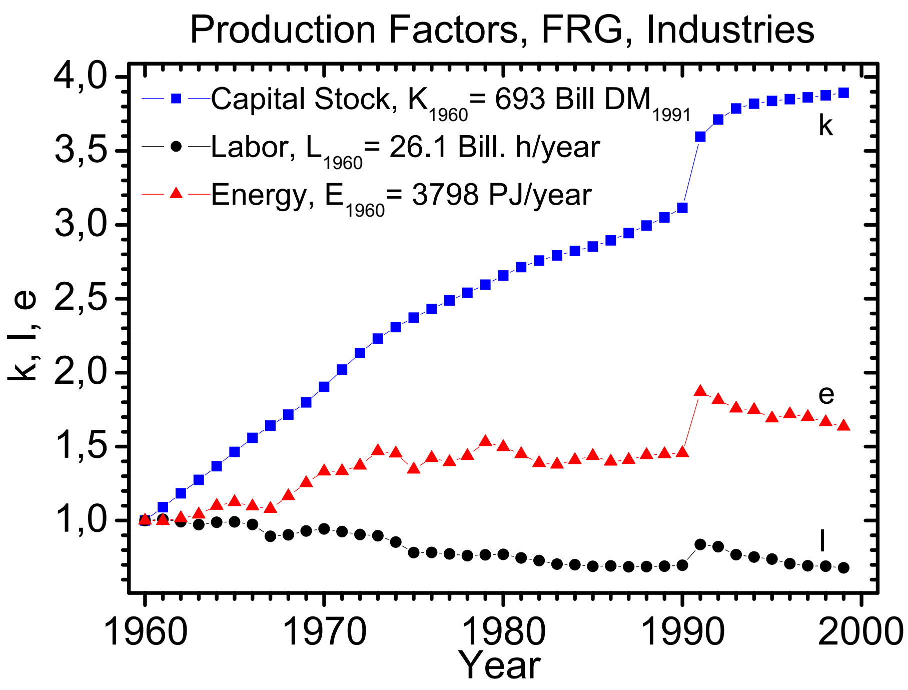
When physics began to matter in economics

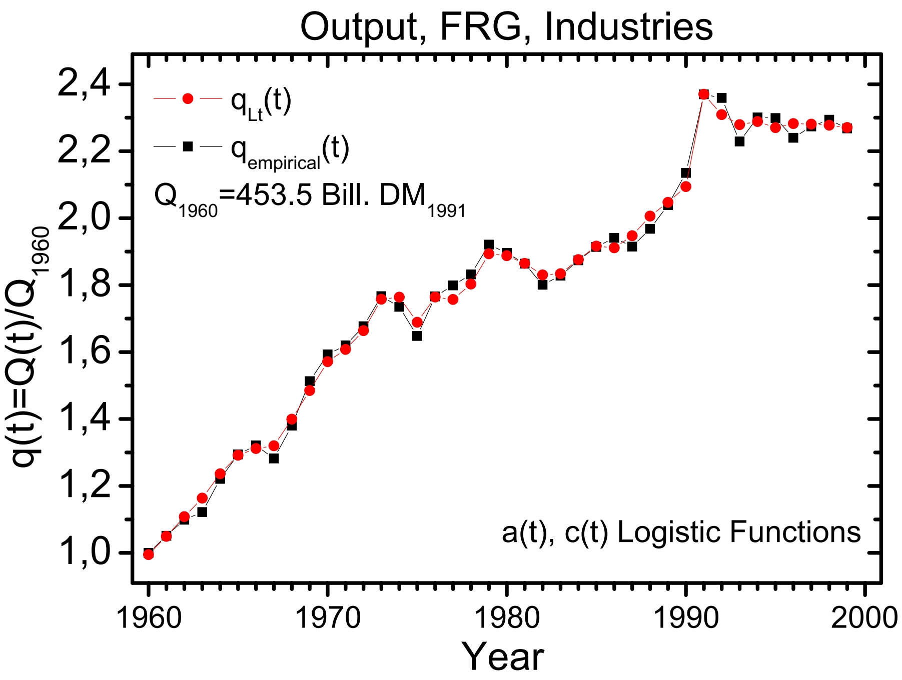


Development of the price of one barrel of crude oil from 1861 to 2011; in 2011 US dollar prices (*upper curve*), and in dollar prices of the day (*lower curve*) Source: http://en.wikipedia.org/wiki/Price_of_petroleum.

1972: “The Limits to Growth”! 1973-1981: Oil price shocks.

Germany, Warenprod. Gewerbe





Left: Empirical time series of capital, labor, and energy.
Right: Growth of output; black: empirical, red: computed with LinEx function.

Economists' views on energy

- "Anything as important in industrial life as power deserves more attention than it has yet received from economists . . . A theory of production that will really explain how wealth is produced must analyze the contribution of the element energy."
  F. G. Tryon, 1927

  "Der entscheidende Fehler der traditionellen Ökonomie ... ist die Außerachtlassung der Energie als Produktionsfaktor."
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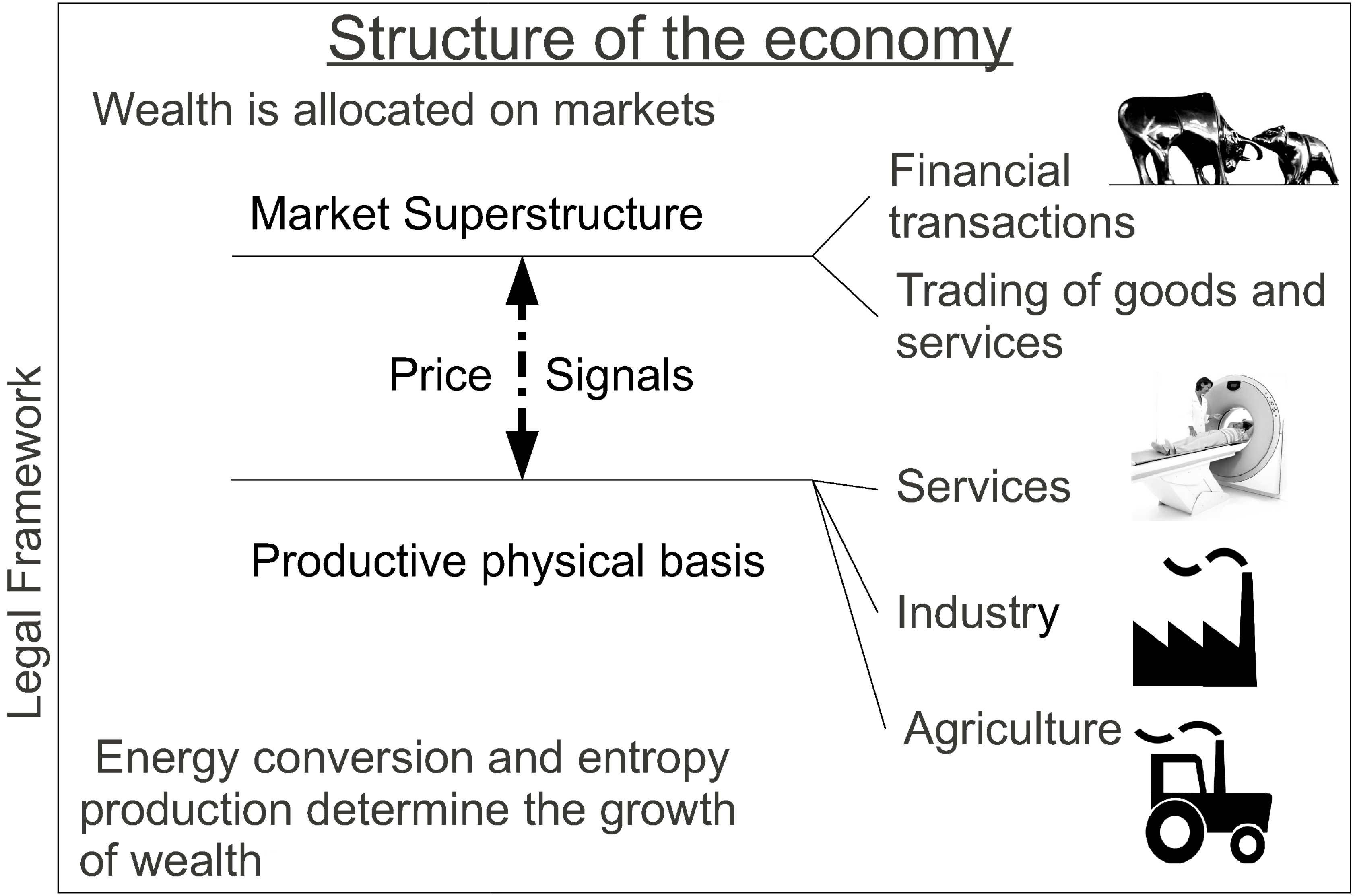
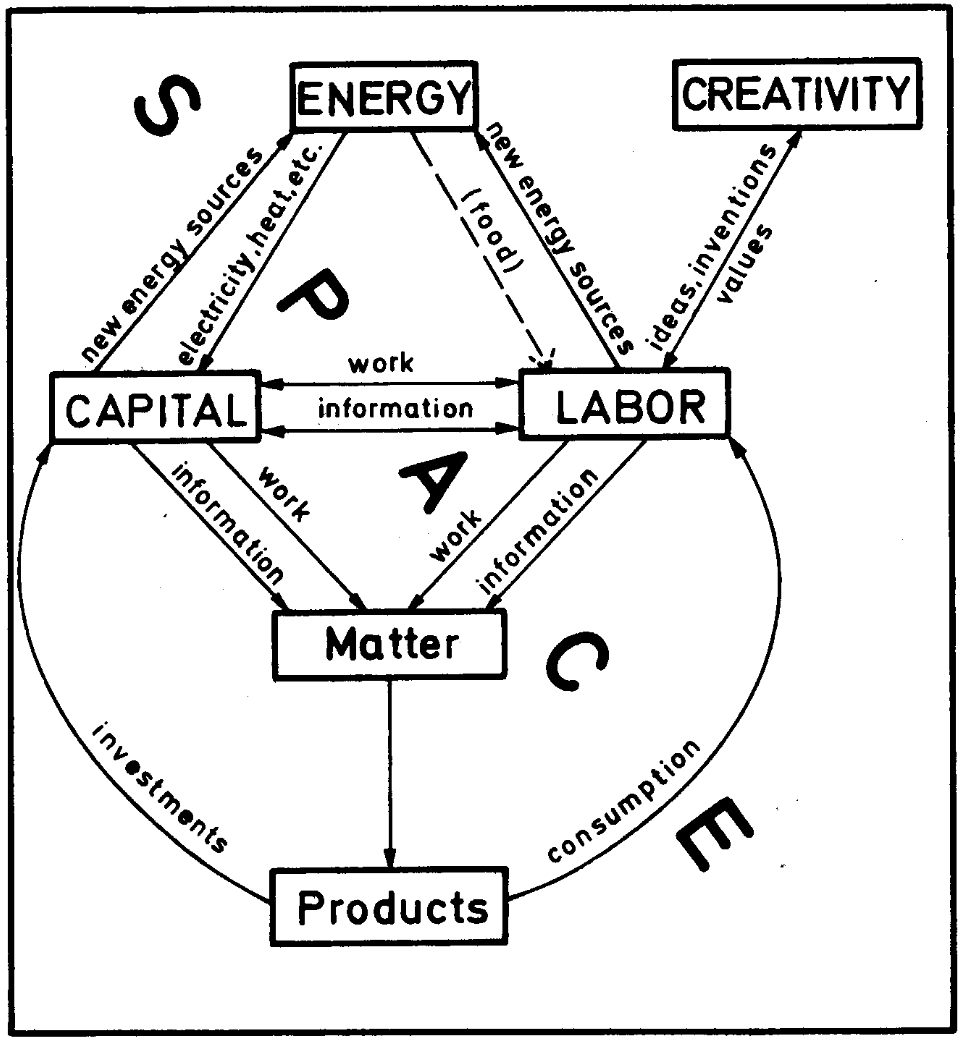
- "The world can, in effect, get along without natural resources", – but: "... if real output per unit of resource is effectively bounded . . . then catastrophe is unavoidable."
  Robert M. Solow, 1974

  "Energy gets about 5 percent of the total input weight in the business sector . . . "
  E. F. Denison (Survey of Current Business, August 1979)

The two levels of the economy



Factors of the productive physical basis



Engineering view, from “The Impact of Energy on Industrial Growth”, Energy 7, 189-203 (1982).

Output, factors and measuring units

- Output Y (measured in constant currency): Gross domestic product (GDP) or part thereof; created by work performance and information processing.

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- Energy E (measured, e.g., in Joules/year) activates the capital stock.
- Creativity C: human ideas, inventions and value decisions that affect the output.
  Assumption: Space, which accomodates production sites, contains resources, and absorbs emissions, stays constant.

KLEC model

see: *Structural Change and Economic Dynamics* **13** (2002) 415-433,
Journal of Non-Equilibrium Thermodynamics **35** (2010) 145-179

Output (value added) and inputs at time t, normalized to their quantities Y_0, K_0, L_0, E_0 in the base year t_0:

$y(t) = Y(t)/Y_0$ (normalized output),

$k(t) = K(t)/K_0$ (normalized capital stock),

$l(t) = L(t)/L_0$ (normalized labor),

$e(t) = E(t)/E_0$ (normalized energy input).

Creativity causes an explicit time dependence of the

production function $y = y(k, l, e; t)$,

which is assumed to be a state function of the economic system (has same mathematical properties as thermodynamic state functions like internal energy and entropy).

Growth equation

No limits to growth in the **past**.
Infinitesimal changes of output, dy, capital, dk, labor, de, and time, dt, are related to each other by the *growth equation*, which is obtained from the total differential of the production function:

$$\frac{\mathrm{d}y}{y} = \alpha \frac{\mathrm{d}k}{k} + \beta \frac{\mathrm{d}l}{l} + \gamma \frac{\mathrm{d}e}{e} + \delta \frac{\mathrm{d}t}{t - t_0} \quad .$$

The **output elasticities**

$$\alpha(k,l,e) \equiv \frac{k}{y}\frac{\partial y}{\partial k}, \quad \beta(k,l,e) \equiv \frac{l}{y}\frac{\partial y}{\partial l}, \quad \gamma(k,l,e) \equiv \frac{e}{y}\frac{\partial y}{\partial e}, \quad \delta \equiv \frac{t-t_0}{y}\frac{\partial y}{\partial t}$$

give the weights, with which relative changes of the production factors k, l, e and of time time t contribute to the relative change of output. In this sense they **measure the productive powers** of capital, labor, energy, and creativity.

Diff. equations for output elasticities

Production functions should be linearly homogeneous in k, l and e at any fixed time $t \rightarrow$ constant returns to scale: $\alpha + \beta + \gamma = 1$. Being state functions, they must be twice differentiable:

$$\begin{aligned}
k\frac{\partial \alpha}{\partial k} + l\frac{\partial \alpha}{\partial l} + e\frac{\partial \alpha}{\partial e} &= 0, \\
k\frac{\partial \beta}{\partial k} + l\frac{\partial \beta}{\partial l} + e\frac{\partial \beta}{\partial e} &= 0, \\
l\frac{\partial \alpha}{\partial l} &= k\frac{\partial \beta}{\partial k}.
\end{aligned}$$

These equations correspond to the Maxwell Relations in thermodynamics. Their most general solutions are:

$$\alpha = A(l/k, e/k), \qquad \beta = \int \frac{l}{k}\frac{\partial A}{\partial l}\mathrm{d}k + J(l/e).$$

Output elasticities

Special solutions of the three coupled differential equations (applying Occam's razor):

- Trivial solutions: constants $\alpha_0, \beta_0, \gamma_0 = 1 - \alpha_0 - \beta_0$.
- Simplest non-trivial solutions, satisfying asymptotic technical-economic boundary conditions:
  $\alpha = a\frac{l+e}{k}$
  (Law of diminishing returns: $\alpha \to 0$, if $(l+e)/k \to 0$),
  $\beta = a(c\frac{l}{e} - \frac{l}{k})$
  (Substitution of capital and energy for labor as automation increases: $\beta \to 0$, if $k \to k_m$ and $e \to ck_m$),
  $\gamma = 1 - \alpha - \beta$
  (At a given point in time the weights with which capital, labor and energy contribute to the growth of output add up to 100 %).

Energy-dependent-CES and nested-CES-function output elasticities are solutions, too.

Production functions

Insert the output elasticities into the growth equation and integrate.

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The constants $\alpha_0, \beta_0, \gamma_0$ yield the energy-dependent Cobb-Douglas production function $y_{CDE} = y_0 k^{\alpha_0} l^{\beta_0} e^{\gamma_0}$.
Neoclassical cost-share weighting:
$\alpha_0 \approx 0.25, \quad \beta_0 \approx 0.70, \quad \gamma_0 \approx 0.05 \longrightarrow$ Solow residual: TP !

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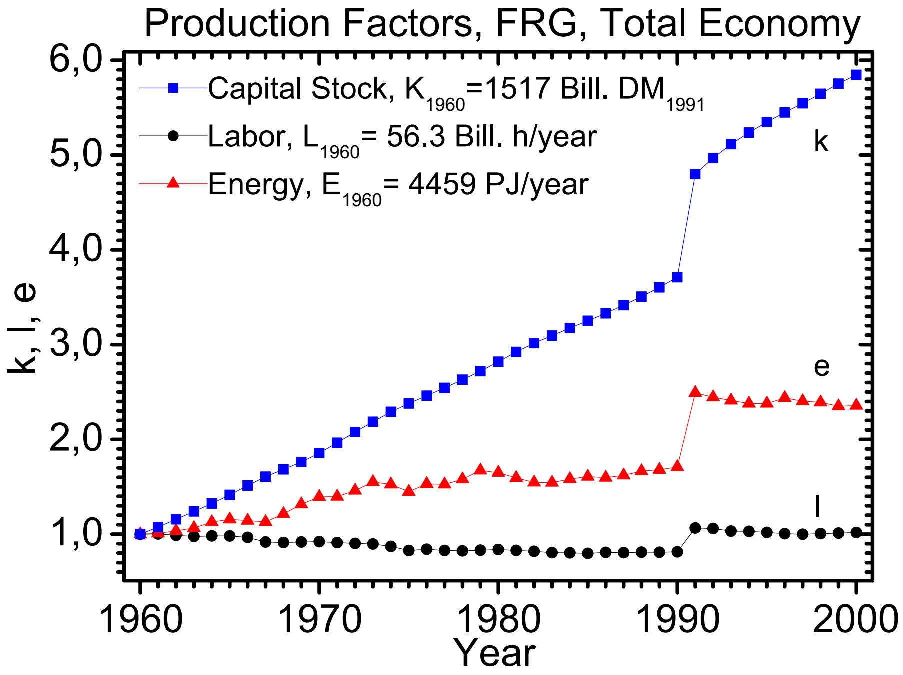
The simplest non-trivial output elasticities yield the **time-dependent LinEx production function**:

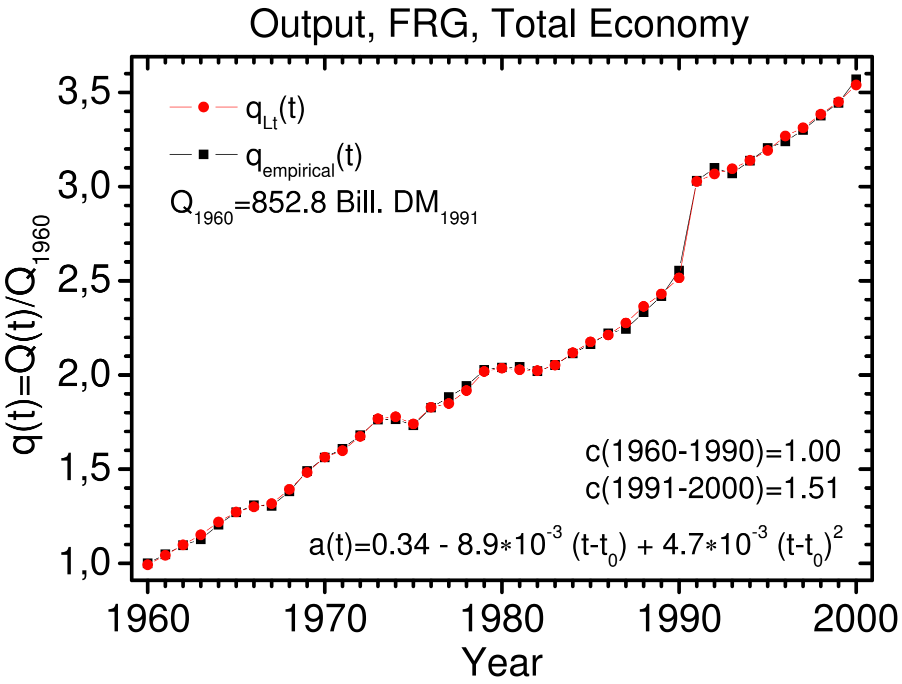
$$y_{Lt}(t) = y_0 e \exp\left[a(t)(2 - \frac{l+e}{k}) + a(t)c(t)(\frac{l}{e} - 1)\right].$$

$a(t)$ = capital-effectiveness parameter, $c(t)$ = energy-demand parameter, modeled by logistics or taylor series, determined by nonlinear (Levenberg-Marquardt) OLS fitting of $y_{Lt}(t)$ to $y_{empirical}(t)$, subject to the constraints: $\alpha \geq 0, \beta \geq 0, \gamma \geq 0$.

Germany, Total Economy

The subsequent results have been obtained in cooperation with
Dietmar Lindenberger, Julian Henn, and Jörg Schmid





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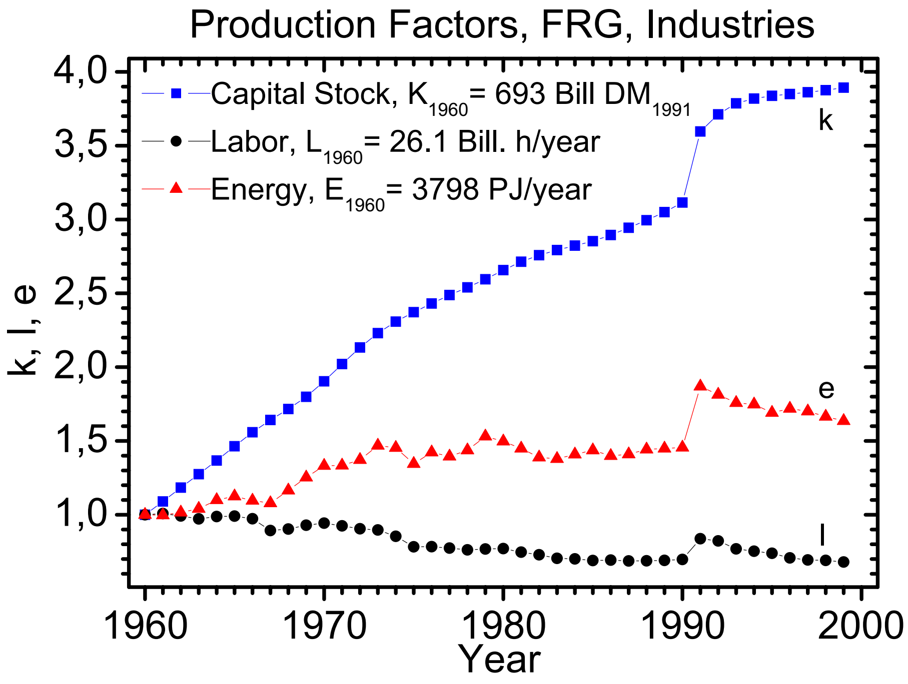

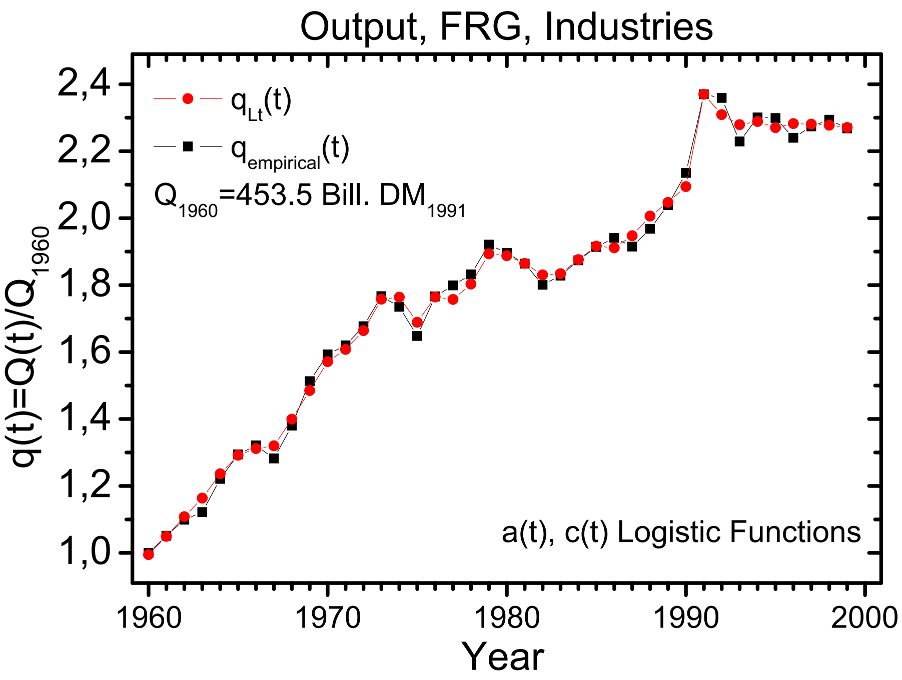

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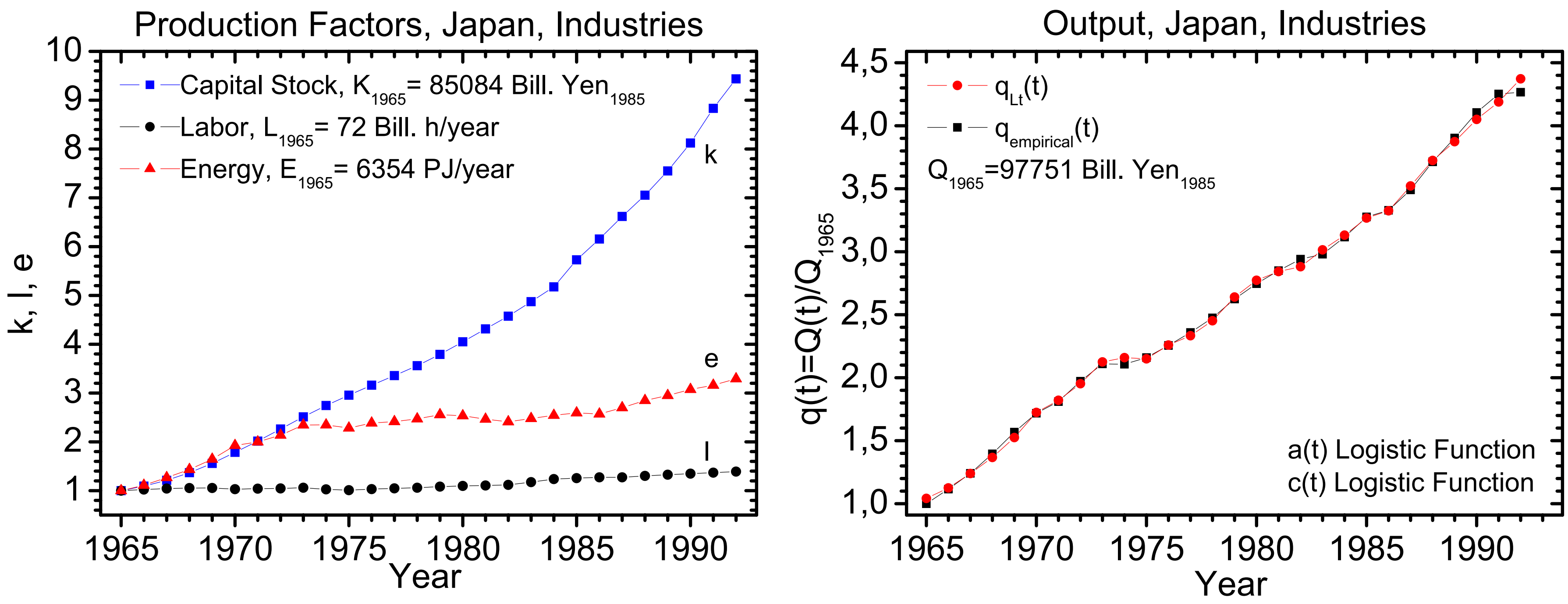
Japan, Industries ≈ Total Economy



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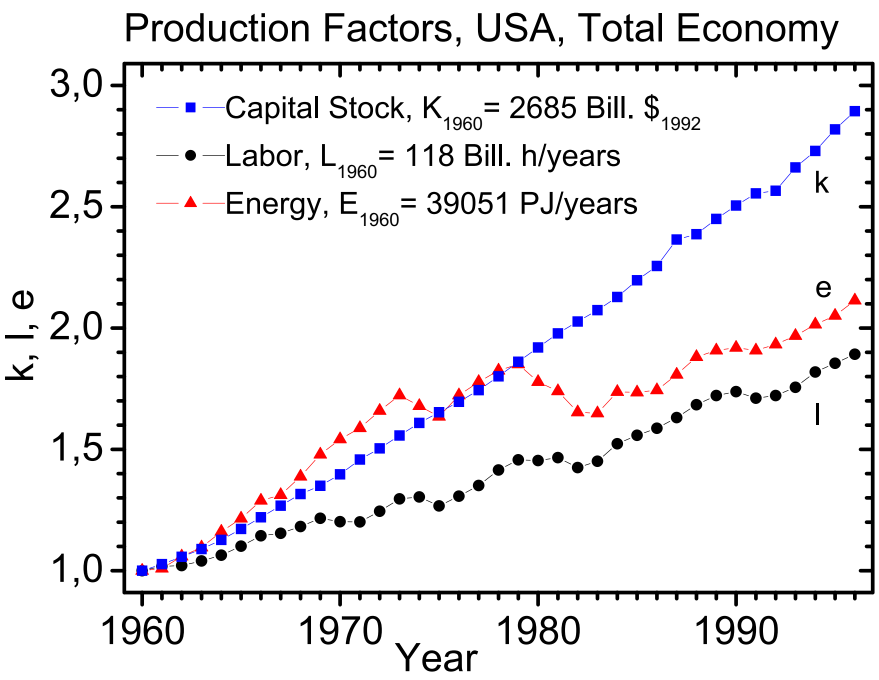
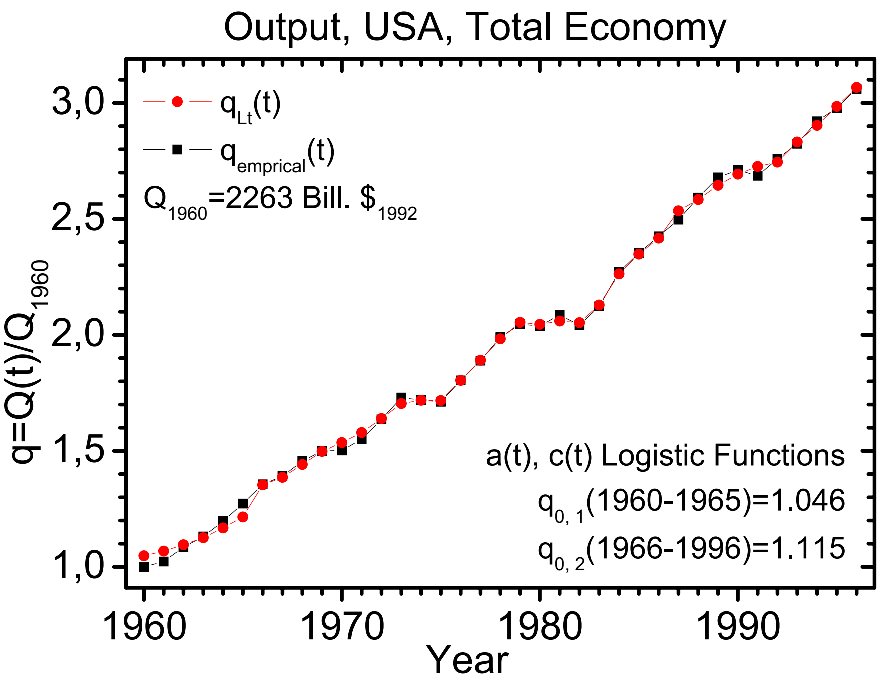
USA, Total Economy





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Output elasticities

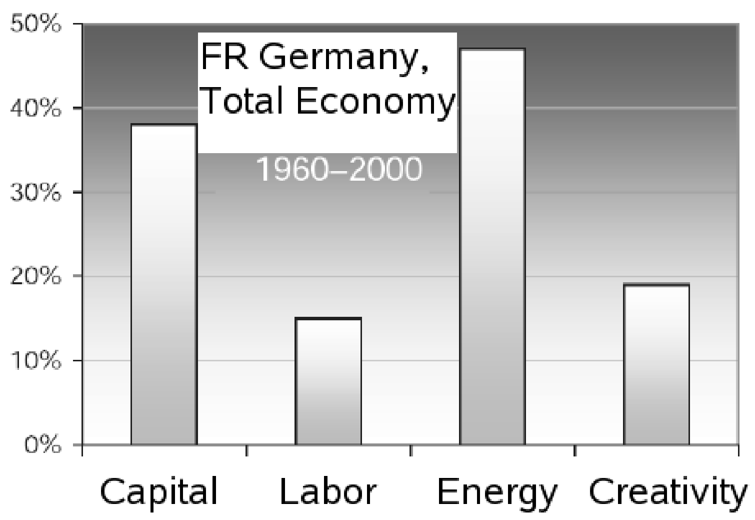
Time-averaged output elasticities (productive powers) of capital ($\bar{\alpha}$), labor ($\bar{\beta}$), energy ($\bar{\gamma}$), and creativity ($\bar{\delta}$)

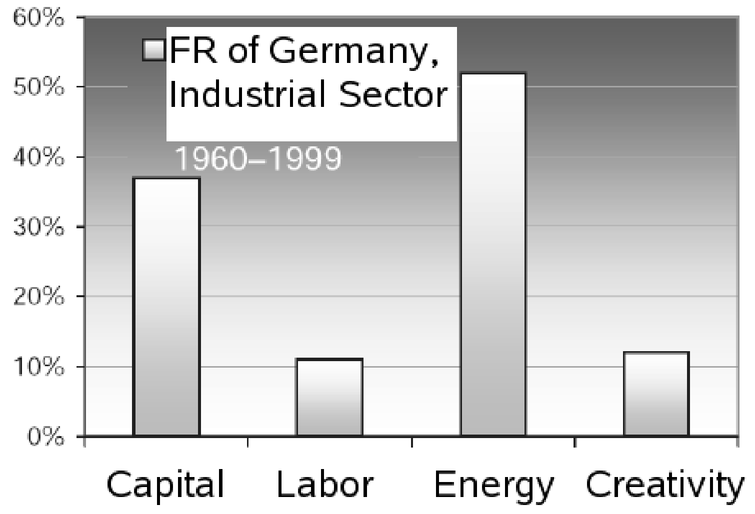
FR of Germany, Total Economy, 1960-2000 ($R^2 > 0.999, D_W = 1.64$):
$\bar{\alpha} = 0.38(\pm 0.09)$, $\bar{\beta} = 0.15(\pm 0.05)$, $\bar{\gamma} = 0.47(\pm 0.1)$, $\bar{\delta} = 0.19(\pm 0.2)$.
FR of Germany, Industries, 1960-1999 ($R^2 = 0.996, D_W = 1.90$):
$\bar{\alpha} = 0.37(\pm 0.09)$, $\bar{\beta} = 0.11(\pm 0.07)$, $\bar{\gamma} = 0.52(\pm 0.09)$, $\bar{\delta} = 0.12^{*}(\pm 0.13)$.
Japan, Industries, 1965-1992 ($R^2 = 0.999, D_W = 1.71$):
$\bar{\alpha} = 0.18(\pm 0.07)$, $\bar{\beta} = 0.09(\pm 0.09)$, $\bar{\gamma} = 0.73(\pm 0.16)$, $\bar{\delta} = 0.14(\pm 0.19)$.
USA, Total Economy, 1960-1996 ($R^2 = 0.999, D_W = 1.46$)
$\bar{\alpha} = 0.51(\pm 0.15)$, $\bar{\beta} = 0.14(\pm 0.14)$, $\bar{\gamma} = 0.35(\pm 0.11)$, $\bar{\delta} = 0.10(\pm 0.17)$.

Ayres/Warr, LinEx with exergy data **USA, 1900-1998**:
$\bar{\alpha} = 0.27$, $\bar{\beta} = 0.09$, $\bar{\gamma} = 0.64$.

Factor cost shares (OECD average) are for
capital: 0.25, labor: 0.70, energy: 0.05

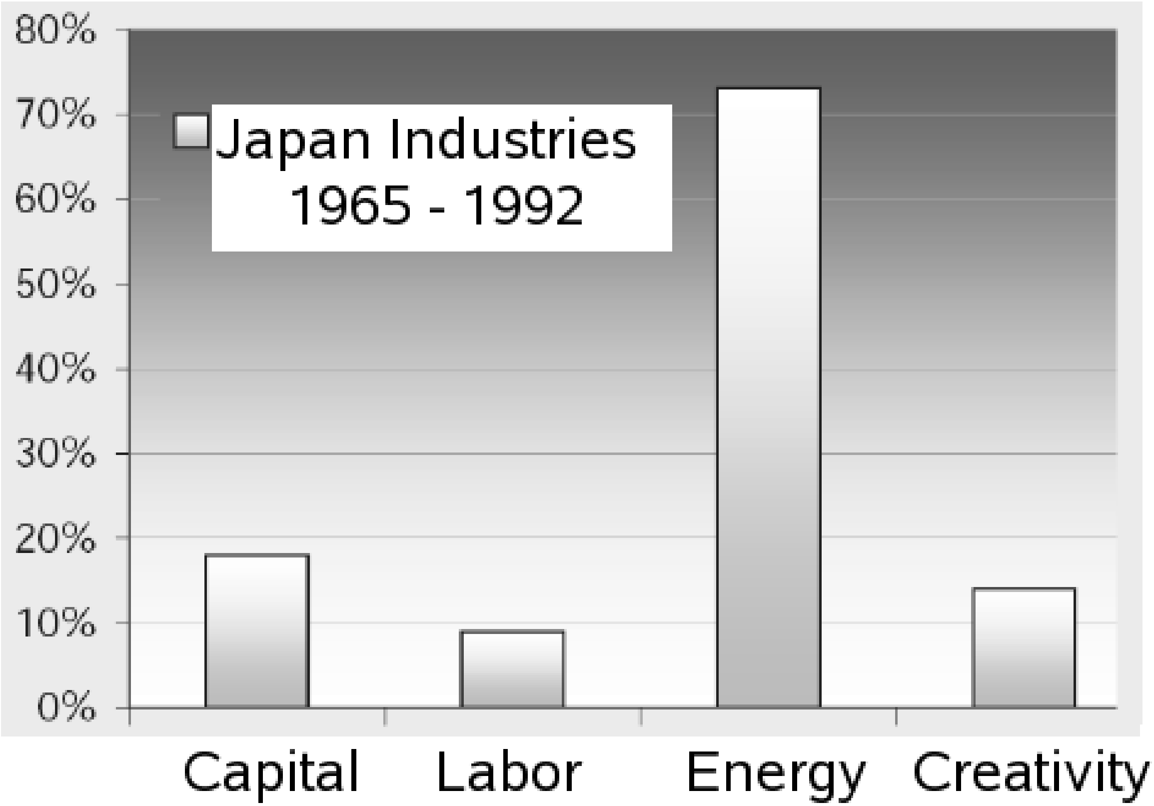
Productive powers: Germany





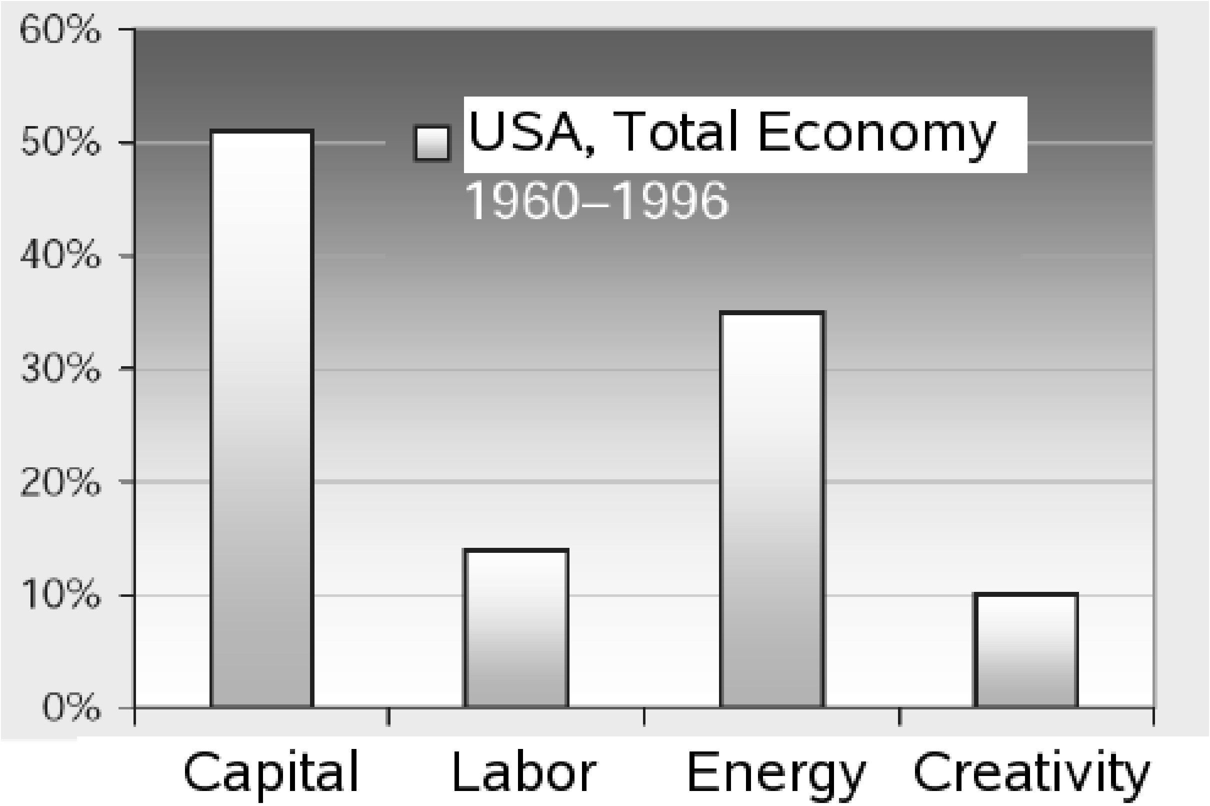
Time-averaged output elasticities (productive powers) in the total economy of the Federal Republic of Germany (top) and in Germany's industrial sector "Warenproduzierendes Gewerbe" (bottom)

Productive powers: Japan



Time-averaged output elasticities in the Japanese sector "Industries", which produces about 90% of Japanese GDP.

Productive powers: USA



Time-averaged output elasticities in the total US economy.

Output elasticities and cost share theorem

N factors of production $X_1 \ldots X_i \ldots X_N$, subject to constraints labeled by a and described by $f_a(X_1 \ldots X_i \ldots X_N, t) \leq 0$.
Optimization of profit (or time-integrated utility) with slack variables yields N equilibrium conditions for the X_i:

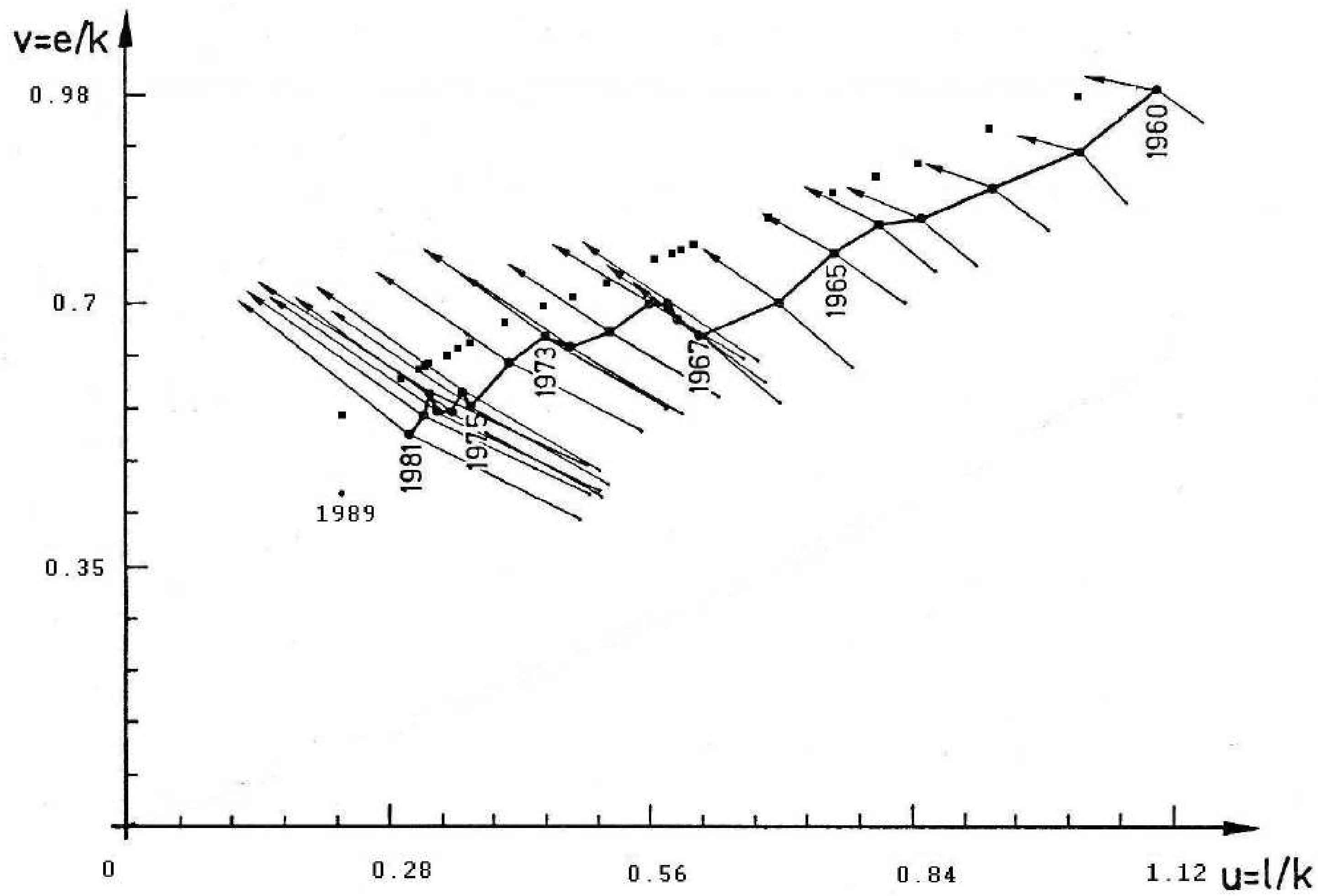
$$\epsilon_i \equiv \frac{X_i}{Y}\frac{\partial Y}{\partial X_i} = \frac{X_i[p_i+s_i]}{\sum_{i=1}^{N} X_i[p_i+s_i]}, \qquad s_i \equiv -\sum_a \frac{\mu_a}{\mu}\frac{\partial f_a}{\partial X_i}.$$

ϵ_i = output elasticity (OE) of Faktor X_i, p_i= market price of unit of X_i; $s_i =$ shadow price of X_i. μ_a/μ = quotients of Lagrange multipliers, depend upon OE. $\longrightarrow$ Output elasticities are not equal to factor cost shares.

$N = 3 : X_1$ **= capital** K**,** X_2 **= labor** L**,** X_3 **= energy** E**.**

Technological constraints on factor combinations: i) degree of capacity utilization $\eta \leq 1$; ii) degree of automation $\leq \rho_T(t) \leq 1$.
a)**Binding, IFF** the state of the economy were **exclusively** determined by profit maximization $\rightarrow$ At least one component of $s_i \neq 0$, less than 3 independent factors. b)**Non-binding**: 3 independent factors, zero shadow prices. **But** technol. and “soft” constraints are “virtually binding”, prevent the economy from reaching the neoclass. optimum.

Non-equilibrium path: Example



Shadow price barrier (squares, from $\eta = 1$) and neg. cost gradients along the path of Germany's industrial sector in the cost mountain between 1960 and 1989, projected onto the $\frac{l}{k} - \frac{e}{k}$ plane.

Path along wall of Chinon fortress

Medieval armies in search of booty might have preferred moving to and looting the city instead of attacking the fortress wall.

Summary and Conclusion

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- In modern economies, energy is a powerful factor of production. We owe a substantial part of our material wealth to energy conversion in the furnaces, heat engines and transistors of the capital stock.
- Inevitably, energy conversion is coupled to entropy production, which, in turn, results in energy depreciation and emissions.
- Energy is cheap and has a high productive power. Labor is expensive and has a low productive power. This results in the pressure to increase automation, substituting cheap energy/capital combinations for expensive labor. It also reinforces the trend towards globalization, because goods and services produced in low-wage countries can be transported cheaply to high-wage countries.

Policy consequence

In order to fight increasing unemployment (and state indebtedness) and stimulate energy conservation and emission mitigation the disequilibrium between the productive powers and cost shares of labor and energy should be reduced by:

- shifting the burden of taxes and levies from labor to energy so that these factors' cost shares come closer to the factors' productive powers; $\rightarrow$ **tax and levy shares:**
  labor 10-20%, capital 30-40%, energy 40-50%.
- Increase of tax per energy unit according to progress in energy conservation in order to keep revenues constant.
- Border tax adjustments according to the energy required for production and transportation of the border-crossing goods prevent competitive disadvantages in relation to not-energy-taxing countries.

No recessions like that due to oil price shocks: the wealth created by energy is not transferred abroad but only redistributed within the country. BBC World Service Poll (2007): People will accept higher energy taxes, if the total tax bill stayed the same.

The German “Energiewende”

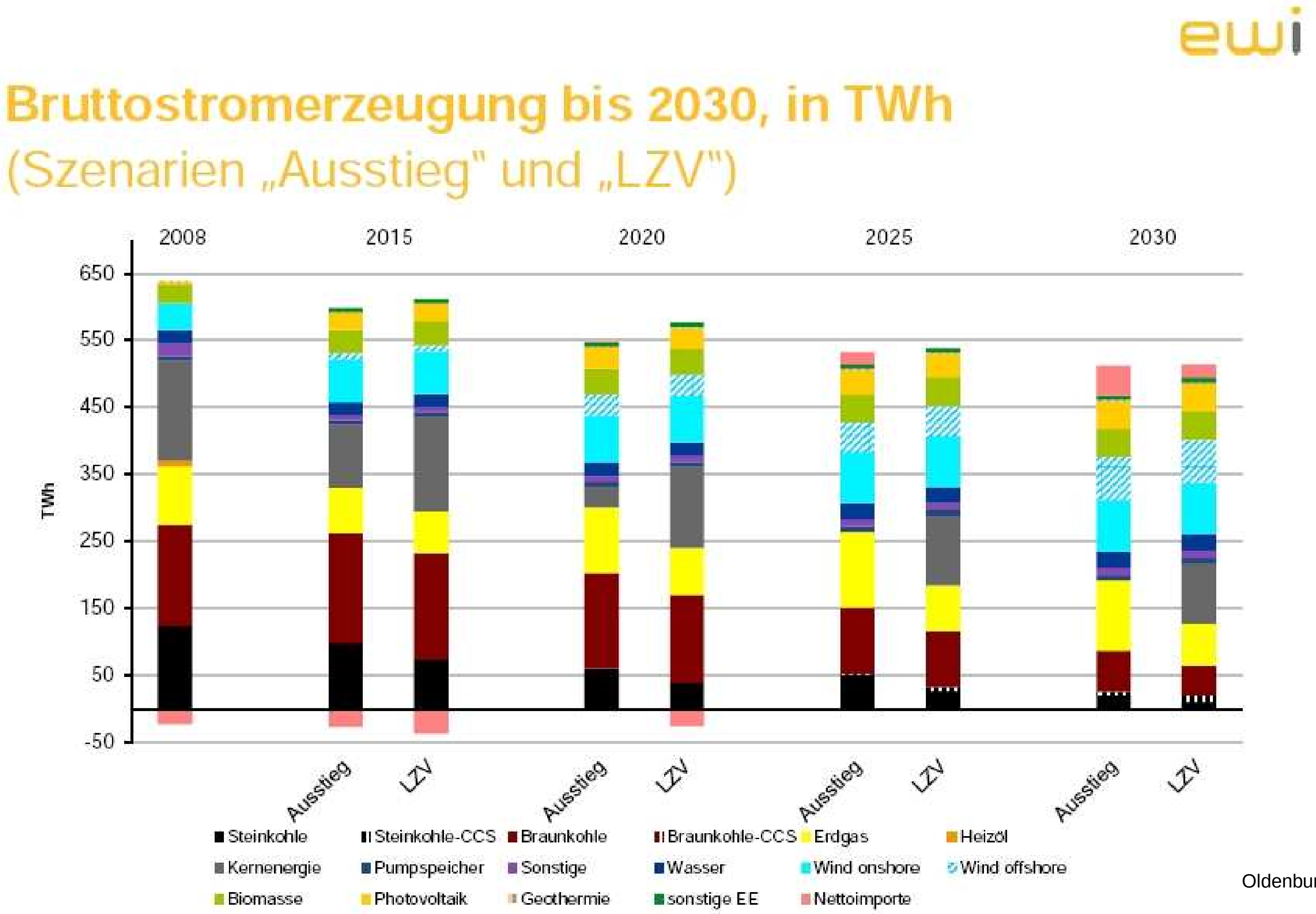
- Before March 2011 (Fukushima catastrophe) Germany decided to extend the operation time of German nuclear power plants (NPP)
  by 8 years for the 7 plants built before 1980 and by 14 years for the remaining 10 NPP: **(LZV = nuclear extension)** .
- After March 2011 Germany opted for
  the immediate shut-down of 8 NPP and phase-out of the remaining 9 until 2022: **(Ausstieg= nuclear exit)**.
- November 2012, Minister of Environmental Affairs Peter Altmeier: “The German energy U-turn is nothing but surgery on the open heart of the economy”.

Risks of nuclear accidents

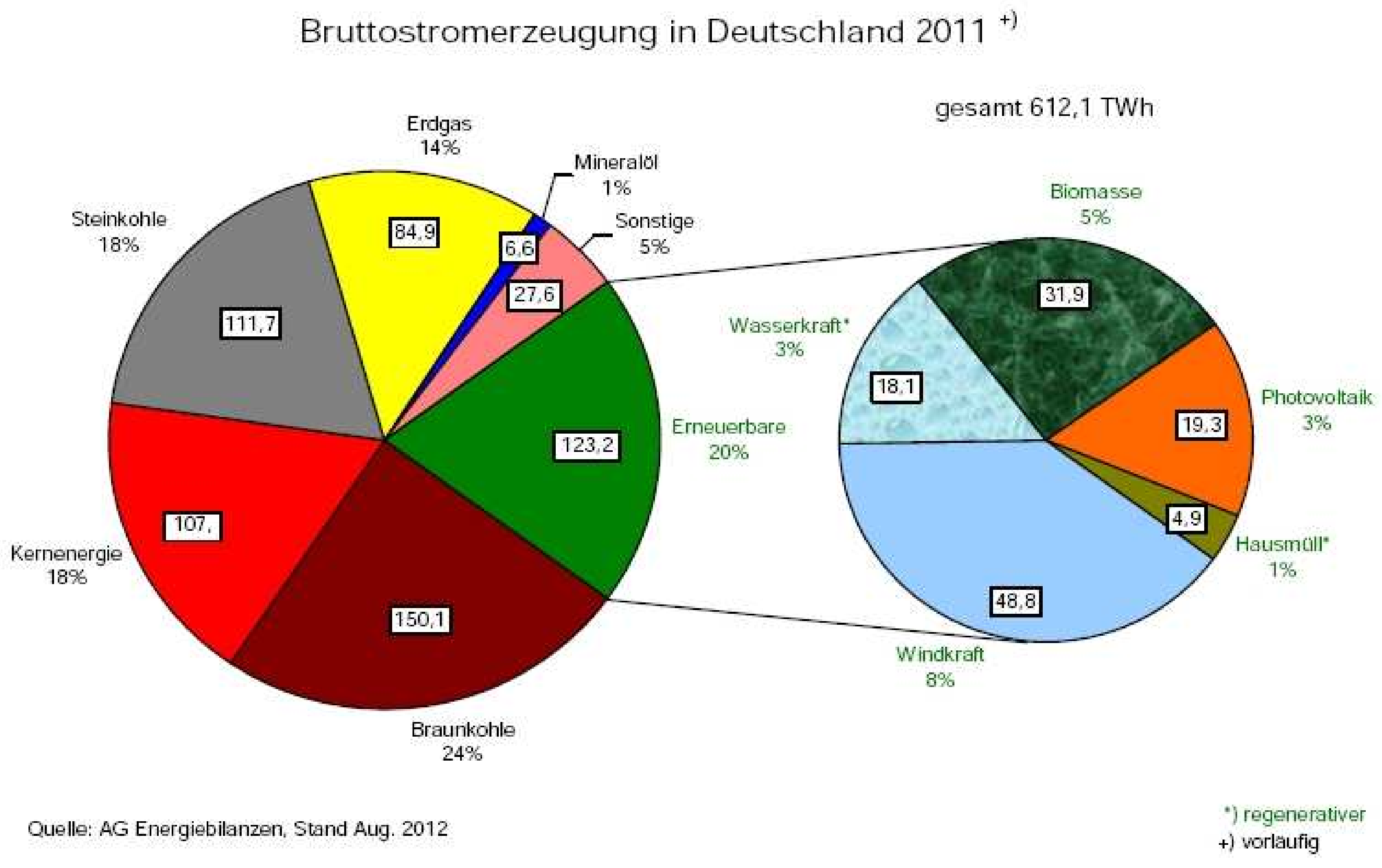
- The German goverment justified its energy U-turn (before important state elections) by the allegedly underestimated residual risk of nuclear power plants (NPP), as shown by the Fukushima accident.
- No underestimated residual risk materialized in Fukushima but rather a well-known, accepted risk due to insufficient design of the NPP against earthquakes and tsunamis. In Germany, a catastrophic process as in Fukushima is as likely as the destruction of the emergency generators of German NPP by a tsunami.
- A catastropic process, as it occurred in Chernobyl on April 26, 1986 in the graphite-moderated RBMK reactor with positive void coefficient, cannot occur in German water-moderated nuclear reactors with negative void coefficients. This is guaranteed by physics.
- The likelihood of a core meltdown in a German NPP is estimated to be one in one million years of reactor operation.

Electricity generation: Government scenarios

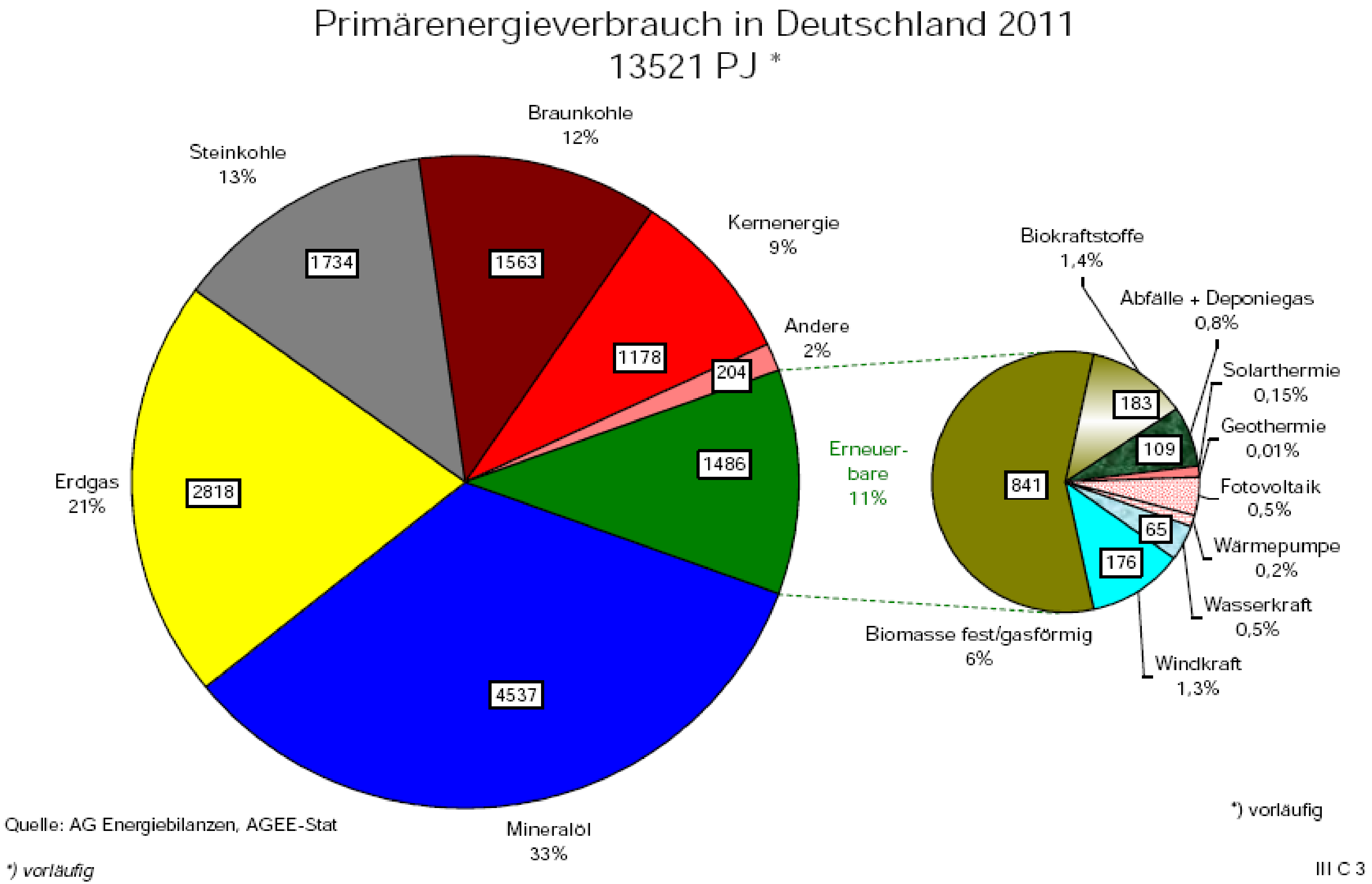
Aim: GHG emissions -40% by 2020, -80% by 2050. $\rightarrow$ energy efficiency increase 2.3 -2.5% p.a.; renewables 36% in electricity generation by 2020, $> 50\%$ of primary energy by 2050.
(Ausstieg= nuclear exit), **(LZV = nuclear extension)**



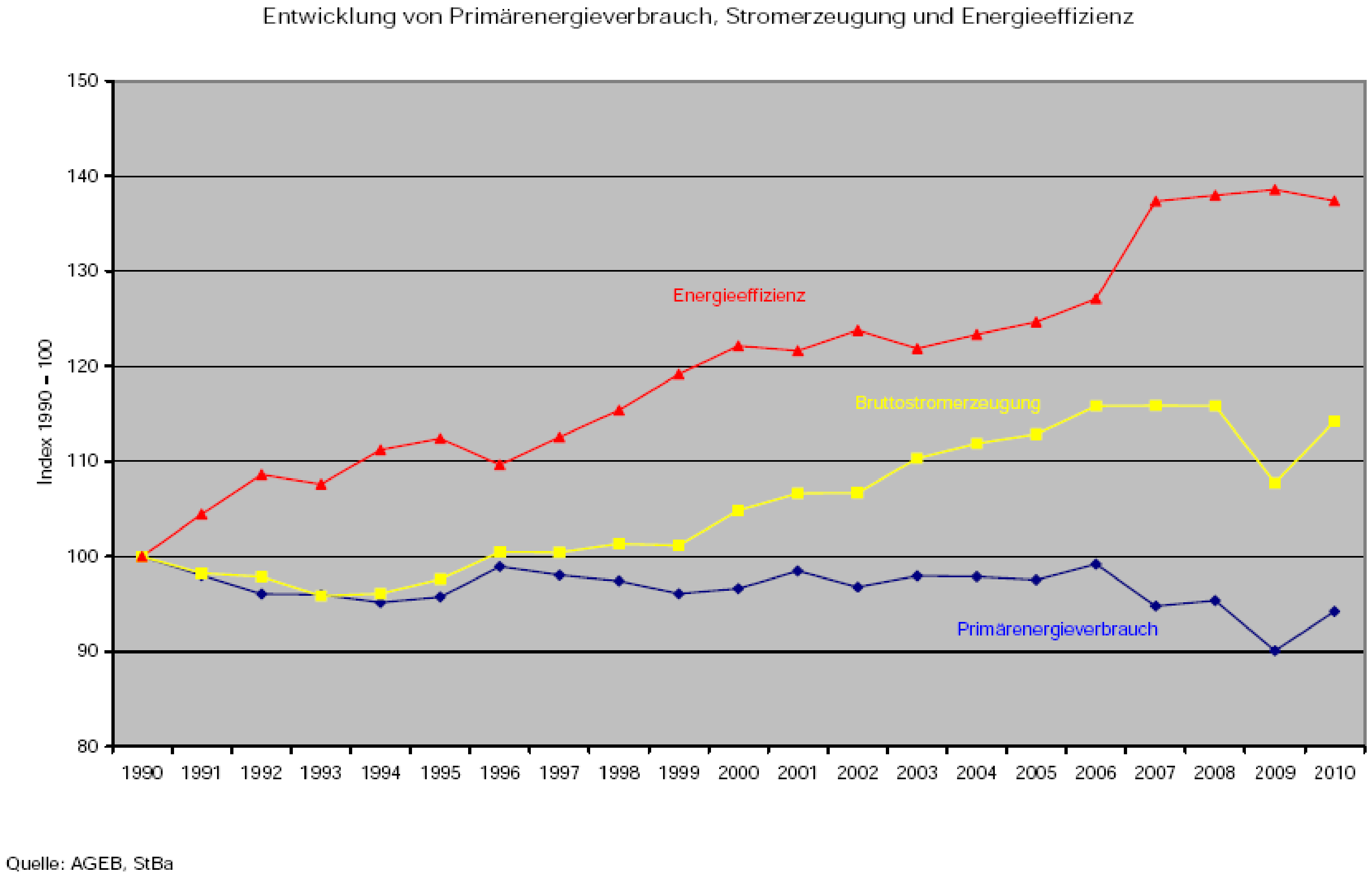
German electricity generation 2011



German primary energy consumption 2011



Energy efficiency increase: phony



German GDP per primary energy quantity (red)

Renewable Energies

Advantage: Earth receives $1.2 \cdot 10^{17}$ Watts from Sun, and most of solar entropy production goes into extraterrestrial space.

Problem: Low energy density of solar radiation $\rightarrow$ need for much capital and land (space).

Hypothetically, Germany's annual primary energy demand (4030 TWh in 2005) might be satisfied
a) by solar cells that cover an area of about 41.000 km^2.
b) by biomass with energetic yields of 78,000 kWh/hectare (intensive chinese farming) on an area of 517.000 km^2.

Chancellor Angela Merkel in 2012:
"On our way into the age of renewable energies we need highly efficient coal and gas power plants during the transition time.... within the next ten years we must build additional power plants with a safely available capacity of 10 GW. "

Problem: fluctuations, EROI

- Fluctuations of sunshine and wind require stand-by gas power plants. In makeshift operation these plants lose money and may be taken off the grid.
- R&D in energy storage is necessary and expensive. Who pays?
- High-voltage DC transmission lines must be built quickly. This demands high investments and is much behind schedule.
- Biomass is supposed to have the lion's share of renewables also in the future. But: biomass has the smallest EROI (< 3), and its production may cause severe ecological and social damages.

Problem: State indebtedness of Germany

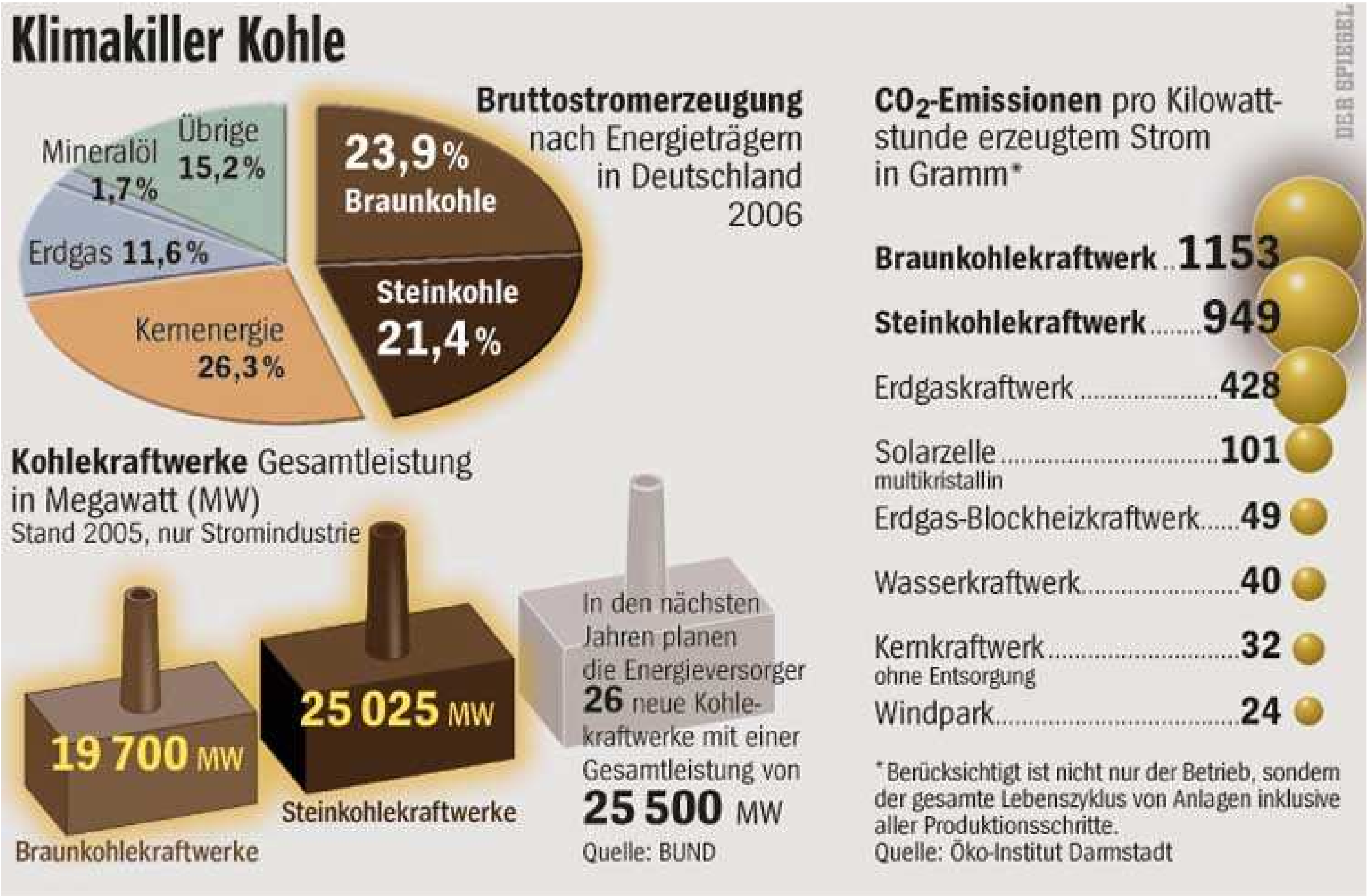
State indebtedness: G7

Gross debt of G7-countries in the year 2009; in national currencies and in percent of gross domestic product (GDP).

Canada	CAD 1,191.29 billions	73%
France	EUR 1,471.02 billions	80%
Germany	EUR 1,853.87 billions	77%
Italia	EUR 1,761.81 billions	115%
Japan	JPY 1,047,730.45 billions	192%
UK	GBP 962.927 billions	68%
USA	US$ 12,093.10 billions	86%

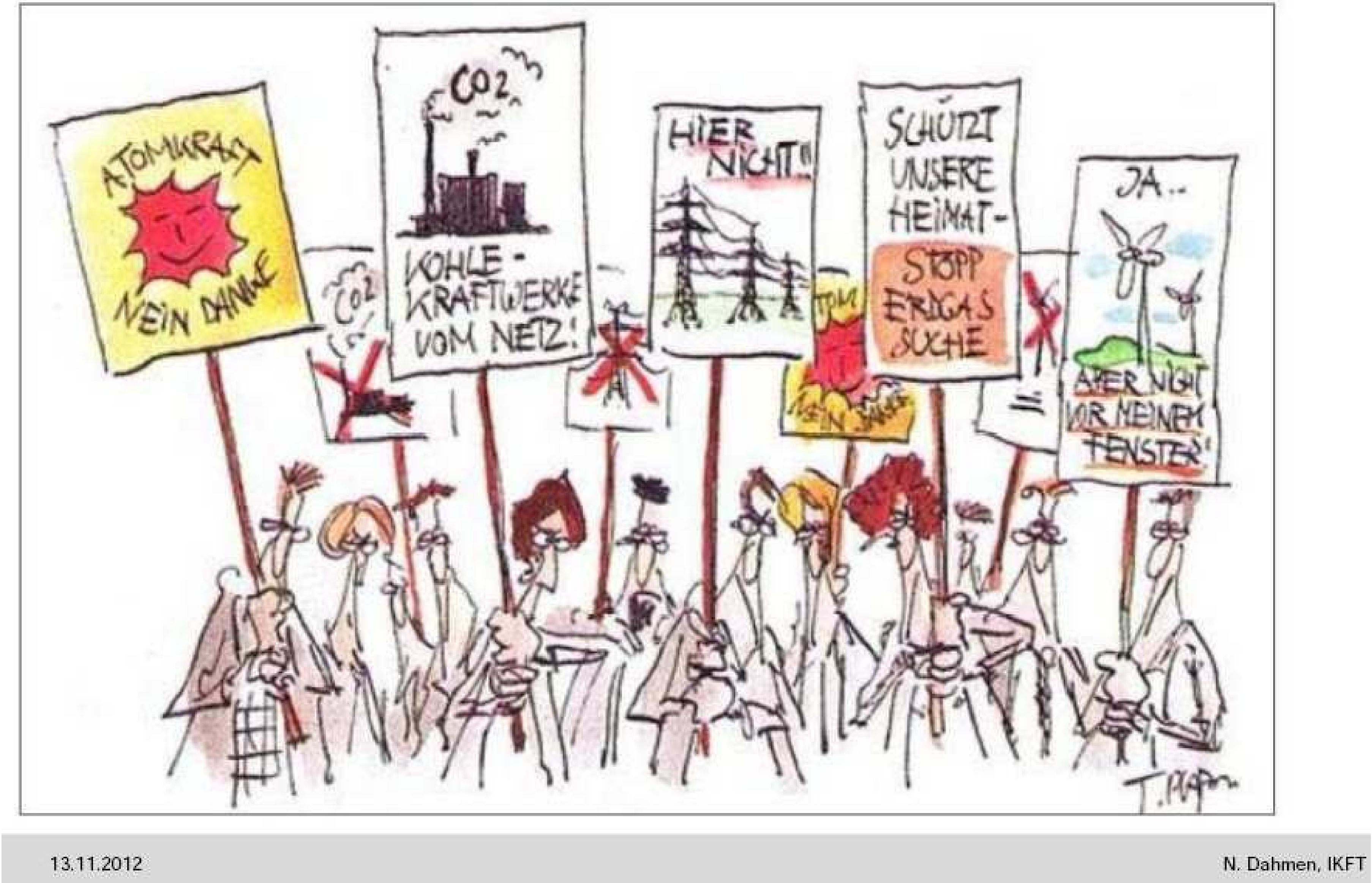
Germany’s gross debt in 2011 exceeds 2000 billions Euro $\equiv$ 82% of GDP.
Constitutional brake on debt: From 2016 net borrowing of the federal government is limited to 0.35% of GDP; same limit holds for the states from 2020. **Hope: Economic Growth**

Problem: life cycle emissions

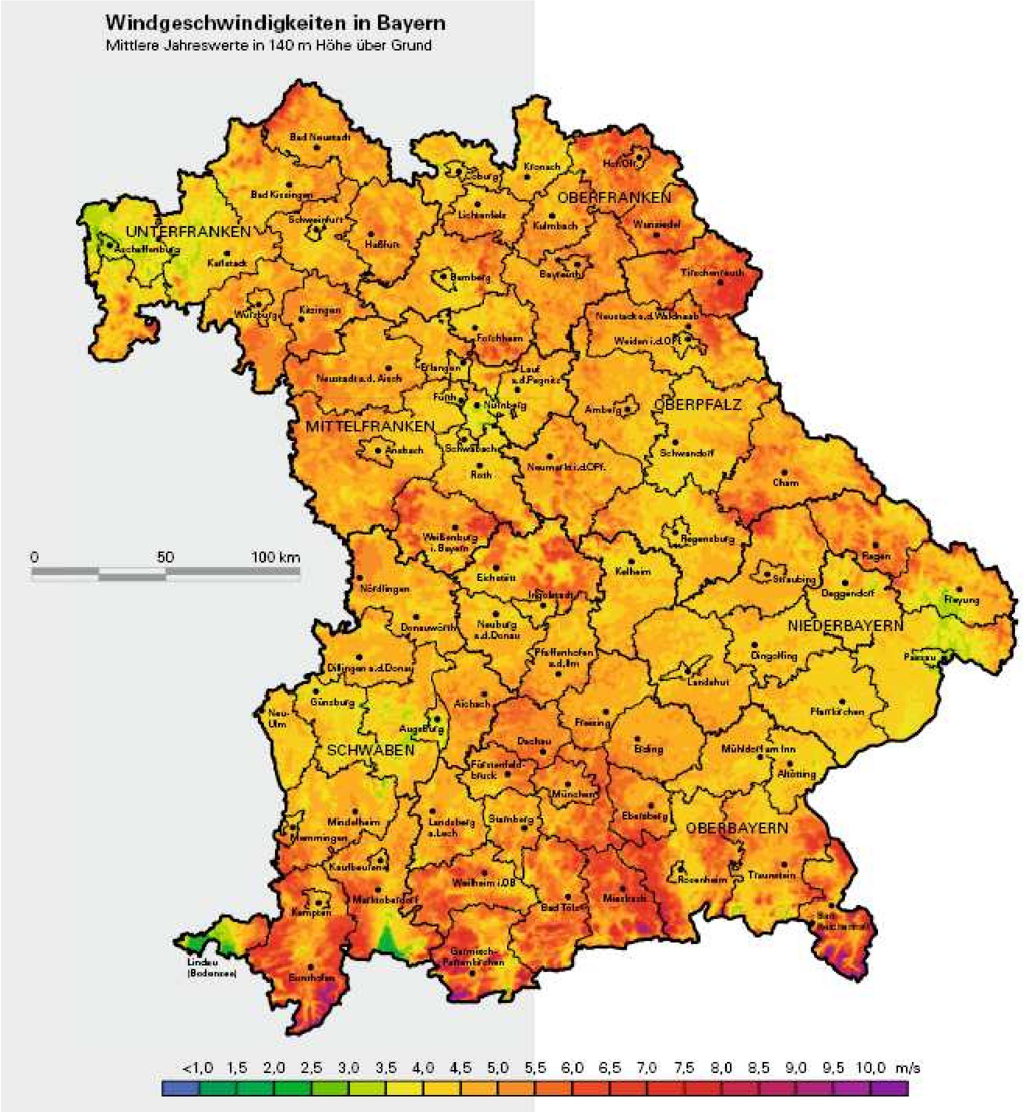


Specific $C0_2$ emissions from various energy sources, in grams per kWh.

Problem: the voters



Problem: NIMBY, Bavarian example



Wind speeds in 140 m above ground. People in Upper Bavaria say:
“Don’t spoil our beautiful landscape by wind turbines”

Conclusion: No easy “Energiewende”

- The sudden U-turn of German energy policy in 2011 was done without identifying a path of sustainable development viable for Germany. The risk is that – once such a path is conceived – the German public might not be willing to accept the required changes in personal life style and the legal framework of the market. This carries the risk that Germany will enhance its CO_2 emissions and/or state idebtedness.

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- If Germans really change their behavior, the opportunity is that Germany will have the competitive advantage of a leader in sustainable energy systems.
- If Germans fail to live up to their ambitious ecological and economic aims, the rest of the world will have the opportunity of learning from our mistakes.