Energy, Entropy, and Economic Growth

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Program

- 1. Energy and entropy
 - (a) Energy conversion and entropy production
 - (b) Emissions and climate change
 - (c) Exergy optimization and technology competition
- 2. Economy
 - (a) The capital, labor, energy, creativity (KLEC) model
 - (b) Economic growth and the economic weights of the production factors
 - (c) Profit (and welfare) optimization subject to the constraints overlooked by neoclassical economics
- 3. Summary, Conclusion, and Scenario Proposal

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

Energy: The fountain of life



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.

Growth of global energy consumption



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

Entropy $\mathbf{S} = \mathbf{k}_{\mathbf{B}} \ln \Omega$: Disorder

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



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Disorder: Example



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 .

Energy conversion and entropy production

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- First Law: Energy = Exergy + Anergy= const. Exergy: valuable part of energy, convertible into useful work. Anergy: useless; e.g. heat dumped into the environment.
- Second Law: unavoidable entropy production
 1) destroys exergy, enhances useless anergy → 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:

 $\sigma_{S,dis}(\vec{r},t) = \sum_{k=1}^{N} \vec{j_k} [-\vec{\nabla}(\mu_k/T) + \vec{f_k}/T] + \vec{j_Q}\vec{\nabla}(1/T) > 0.$ $\vec{j_k} = \text{particle current density}, \vec{j_Q} = \text{heat current density},$ $(\vec{\nabla}: \text{ gradient}, T = \text{temperature}, \mu_k = \text{chemical potentials},$ $\vec{f_k} = \text{external forces.})$ Air pollution (China!), climate change

Global GHG emissions in 1990



Abb. 3: Ursachen des zusätzlichen Treibhauseffektes: Gerundete Anteile durch die Bereiche, die zuvor erläutert sind (vgl. Tab. 1 und 2)

Global GHG emissions in 2000



Fossil-fuel CO $_2$ emissions 1990–2010



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

German energy-related \mathbf{CO}_2 emissions

Energiebedingte CO2-Emissionen in Deutschland



Quelle: Umweltbundesamt

erste Schätzung

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.

Global Warming



Variations of the average surface temperature of Earth during the last 10.000 years.

Scenarios for exergy optimization

deeco





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

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

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- 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

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).

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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):

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

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 must be twice differentiable and linearly homogeneous in k, l and e at any fixed time $t \rightarrow$ constant returns to scale, i.e. $\alpha + \beta + \gamma = 1$, and

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

The most general solutions of these equations are:

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

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 %).

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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:

 $\alpha_0 \approx 0.25, \quad \beta_0 \approx 0.70, \quad \gamma_0 \approx 0.05 \rightarrow \text{Solow residual.}$

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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



Germany, Warenprod. Gewerbe



Japan, Industries \approx Total Economy



USA, Total Economy



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: $\bar{\alpha} = 0.27, \qquad \bar{\beta} = 0.09, \qquad \bar{\gamma} = 0.64.$

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.

Optimization and cost share theorem

N factors of production $X_1 \dots X_i \dots X_N$, subject to constraints labeled by a and described by $f_a(X_1 \dots X_i \dots X_N, t) = 0$.

Optimization of profit (or time-integrated utility) 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 $\leq \rho_T(t) \leq 1$. Binding, IFF the state of the economy were **exclusively** determined by profit maximization \rightarrow a) At least one component of $s_i \neq 0$, b) less than 3 independent factors. Non-binding, if the real-world state of the economy is **NOT** exclusively determined by profit maximization \rightarrow a) equilibrium conditions don't apply, b) 3 independent factors.

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.

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- 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.

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- These facts should shape the instruments in the scenario toolbox.

Proposal for scenario design

Fossil fuels satisfy roughly 80% (mineral oil 33%) of present world energy demand ($1.72 \cdot 10^{17}$ W).

- Build a three-sector model of the economy's physical basis, consisting of 1) Agriculture, 2) Services, including transportation, 3) Industries.
- Describe the outputs of 1), 2), and 3) by appropriate time-dependent, twice-differentiable production functions in capital, labor, and energy.
- Estimate all output elasticities econometrically. Model their response to future energy price increases in scenarios of A) (sudden) resource scarcities and, alternatively, B) ecological tax reforms that shift the burden of taxes and levies from labor to energy. Model the coupling between the outputs of 1), 2) and 3). Model the interdependence of economic growth, employment and pollution.
- Compute the scenarios. Include options where nuclear and renewably generated electricity, hydrogen or methane substitute for fossil fuels.

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; → 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)



Bruttostromerzeugung bis 2030, in TWh (Szenarien "Ausstieg" und "LZV")



German electricity generation 2011





Quelle: AG Energiebilanzen, Stand Aug. 2012



German primary energy consumption 2011



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Energy efficiency increase: phony

Entwicklung von Primärenergieverbrauch, Stromerzeugung und Energieeffizienz



Quelle: AGEB, StBa

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 km². b) by biomass with energetic yields of 78,000 kWh/hectare (intensive chinese farming) on an area of 517.000 km².

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



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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

Klimakiller Kohle



CO ₂ -Emissionen pro Kilow stunde erzeugtem Strom in Gramm*	att-
Braunkohlekraftwerk 11	53
Steinkohlekraftwerk9	49
Erdgaskraftwerk4	28
Solarzelle	101
Erdgas-Blockheizkraftwerk	.49 🔴
Wasserkraftwerk	.40 🥚
Kernkraftwerk	.32 🥚
Windpark	.24 🥥

* Berücksichtigt ist nicht nur der Betrieb, sondern der gesamte Lebenszyklus von Anlagen inklusive aller Produktionsschritte. Quelle: Öko-Institut Darmstadt

Specific CO_2 emissions from various energy sources, in grams per kWh.

Problem: the voters



N. Dahmen, IKFT

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 CO₂ 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.