ESA-1

Introduction to Energy Systems

Energy Systems

Interaction between:
-- Society
-- Economy
-- Technology
-- Policy
that shape both
-- Demand
-- Supply
in terms of quantity, quality, costs, impacts.

Definitions & IS Units

- Energy: Capacity to do work
- Power: Rate of energy transfer

- Newton (N): 1 kg m/s^2 (force)
- Joule (J): 1 N applied over 1 m (energy)
- Watt (W): 1 J/second (power)

- Example: 1 HP = 745 W (745 J/s)
  for 1 hr = 0.745 kWh

Examples of Power and Energy

(ranked by power ratings)

	Power W	Time Sec's	Energy J (W/s)
Solar energy to earth per year	1.8 E 17	3.2 E 7	5.5 E 24
Earthquake 8 Richter scale	2.0 E 15	3.0 E 1	6.0 E 16
Global energy use for 2000	1.4 E 13	3.2 E 7	4.4 E 20
Thunderstorm (kinetic energy)	1.0 E 11	1.2 E 3	1.2 E 14
Space shuttle lift-off	1.2 E 10	1.2 E 2	1.4 E 12
B 747 flight Tokyo-Frankfurt	1.1 E 8	4.0 E 4	4.4 E 12
Energy/day for a supermarket	2.0 E 5	4.3 E 4	8.6 E 9
Daily metabolism of adult	1.0 E 2	8.6 E 4	8.6 E 6
Burning a small candle	3.0 E 0	1.8 E 3	5.4 E 3

E = exponent to basis 10, i.e. E 2 = 10^2 = 100

Energy Systems Analysis Based on Smil, 1991

Some Orders of Magnitude (EJ = 10^{18} J)

5,500,000 EJ Annual solar influx

1,000,000 EJ Fossil occurrences

50,000 EJ Fossil reserves

440 EJ World energy use 2000

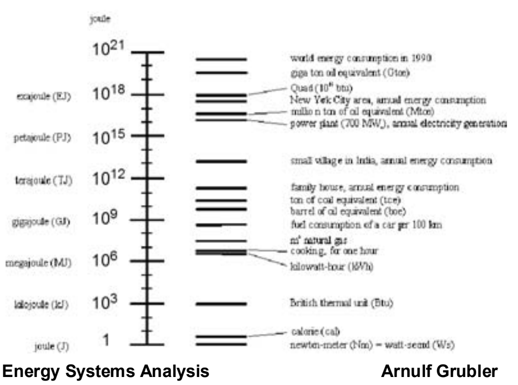
<1 EJ NY city energy use/yr

0.000004 EJ B-747 flight Tokyo-Frankfurt

Energy Systems Analysis **Arnulf Grubler**

Energy Units and Scales

(Source: IPCC Energy Primer)



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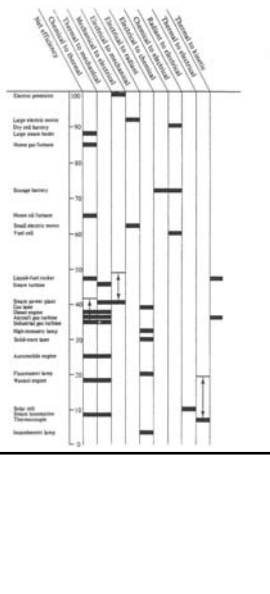
Rough Equivalences

10 Gtoe	=	420 EJ
1 Gtoe	=	42 EJ
1 Quad	=	1 EJ
1 Mtoe	=	42 PJ
1 toe	=	42 GJ
1 boe	=	6 GJ
1 m3 gas	=	40 MJ
1 kWh	=	4 MJ
1 Btu	=	1 kJ

Energy Flow Characteristics

- Physical: chemical, kinetic, electric, radiant,…
- Processing depth: primary→secondary→final
- Transaction levels: producer→producer producer→consumer consumer→consumer (future?)
- System boundaries: secondary→final→useful→service



Examples of Energy Conversions, Devices and (1st Law) Efficiencies

Source: SciAmer, 1972

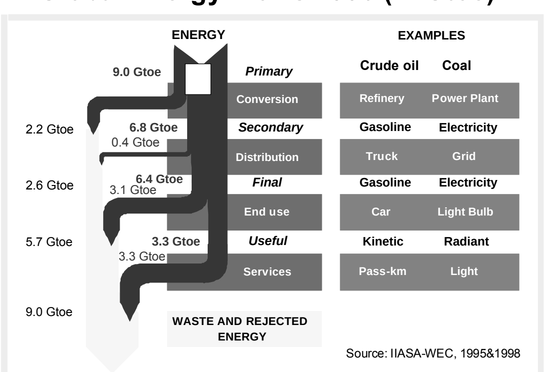
What means….

- Primary energy: Resources as extracted from nature (crude oil, solar heat)
- Secondary energy: Processed/converted energy (gasoline from crude oil, electricity from coal or hydropower)
- Final energy (as delivered to consumer)
- Useful energy (converted by final appliances (heat from radiator, light from bulb)
- Services = actual demand: comfort, illumination, mobility,… (units ephemeral)

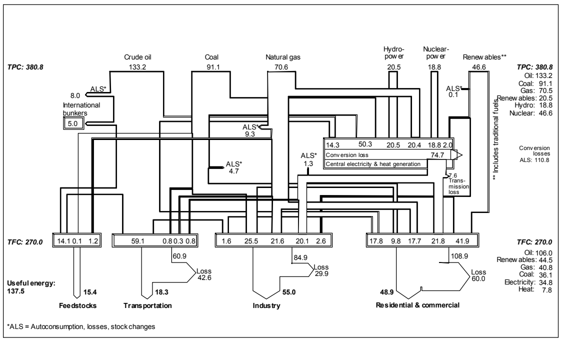
System Boundaries

- Energy sector: Primary→ Final (domain of supply bias)
- Energy end-use: Final→Useful (domain of consumer bias)
- Energy Integration (IRM, LC): Primary→Useful/Services
- Full Integration (IA): Whole environment (incl. “externalities”)

Global Energy Flows 1990 (in Gtoe)



Global Energy Flows (EJ in 1990)



Laws of Thermodynamics (no policy can escape from)

- 1st (conservation) Law
- 2nd (entropy) Law

Thermodynamically, no machine (conversion process) operates in a closed system: i.e. energy exchanges with the environment (friction losses, waste heat)

Perpetuum Mobile: Impossible in a Thermodynamically Open System

Laws

- 1^{st} (conservation) Law: In closed system: energy can neither be created or destroyed
  BUT: Energy devices generally operate in open system (→1^{st} Law efficiency)
- 2^{nd} (entropy) Law: General movement towards lower form values of energy
  (e.g. electricty→high temp.heat→low temp.heat), or increase in 'disorder' (entropy);
  e.g. candle = flame→light→heat (flame→room)
  MIND: Efficiency depends on adequacy of energy form value for task at hand (→2^{nd} Law efficiency)

Energy Efficiency 1

1^{st} Law efficiency:
Ratio of energy output to input;

Varying systems boundaries:
Conversion (gas furnace): ~100% (gas→heat)
Device (furnace+exhaust)*: 90%
Final/Useful (furnace→radiator): 60-80%
Total system (house heating): ~5% (→2^{nd} Law)

*Without latent heat from condensation = LHV
Including latent heat from condensation = HHV

Energy Efficiency 2

2^{nd} Law efficiency: Minimum amount of exergy required for a particular task / actual exergy spent in completing the task

Exergy = availability (capacity to do *useful* work) = inverse of entropy

Hence: Quality and adequacy matters.

Examples for 2nd Law Efficiency

$$\mathrm{I}\ (T - T_0)\ /\ T\ \mathrm{I}$$

Home heating: outside temp. = 0 °C

desired indoor = 21 °C

= I (273K-294K)/273K I = 0.077 = 8%

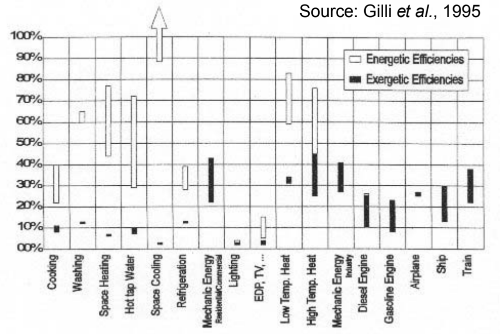
Cont. glass furnace (gas) = 1500 °C

float glass out = 21 °C

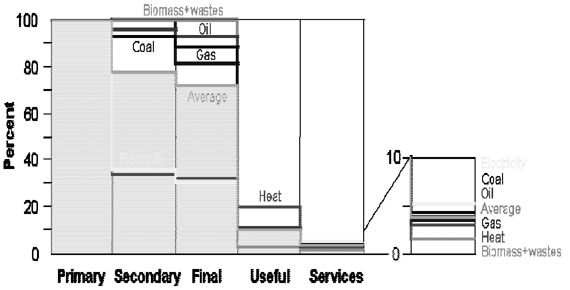
= I (1773K-294K)/1773K I = 0.83 = 83%

First and Second Law Efficiencies of Energy Conversion

Source: Gilli *et al.*, 1995



WORLD-Exergy Efficiency (as percent of primary exergy)



Implications:

Rules of thumb for engineers and policy makers

- Largest leverage: Extending system's boundary for designs and policies
- Look at exergy rather than energy alone
- Largest possible efficiency gains (x20): End-use and service efficiency, heat cascading (industrial symbiosis)

BUT:

- Efficiency not all (→valuation)
- Main scope outside energy engineering/policy: Architecture, urban & transport planning, lifestyles,….

Energy Systems Constraints: Integration Demand - Supply

Physical

- Matching form value
- Matching spatial scales
- Matching temporal scales

Societal: Availability of:

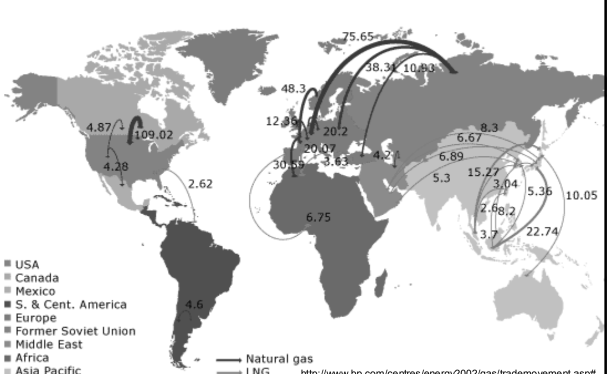
- Capital
- Information
- Incentives
- Policy attention

Energy Constraints

- Spatial mismatch supply-demand: World trade in fuels ~630 Billion $ (~50% of all primary products exports)
- Temporal mismatch supply-demand (load curves): Need for storage & interconnection (capital intensive)
- Magnitude mismatch supply-demand: Power densities, e.g. renewables vs. urban energy use

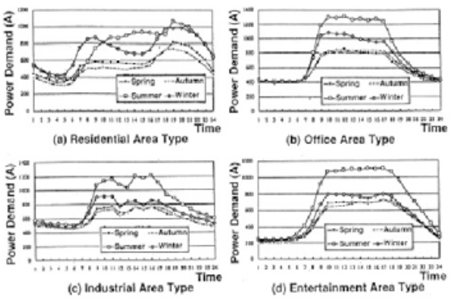
map of major gas trade movements

Trade flows worldwide (billion cubic metres)



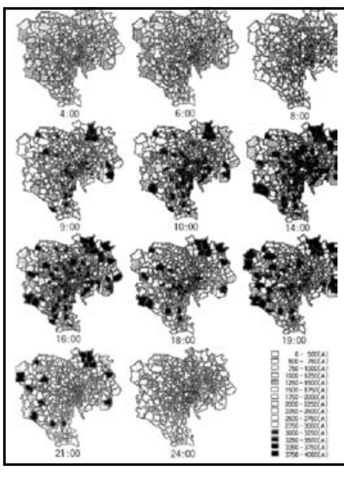
http://www.bp.com/centres/energy2002/gas/trademovement.asp#

Load Curves: Tokyo



Source: Mogouro et al., 2002

Energy Systems Analysis **Arnulf Grubler**



Linking Space and Time in Tokyo: Power Density of Demand

Source: Mouguro et al., 2002

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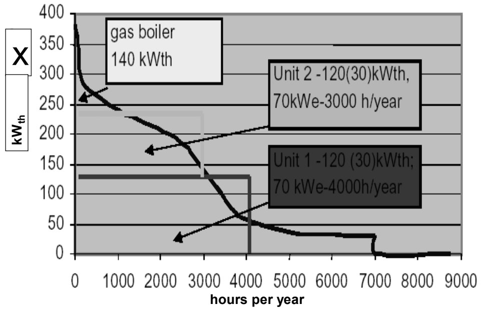
Heat Load Curve of a Hotel in Austria Supplied by Cogeneration



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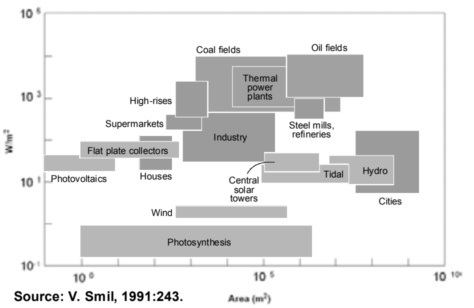
Spatial Power Densities of Energy Production and Consumption



Source: V. Smil, 1991:243.

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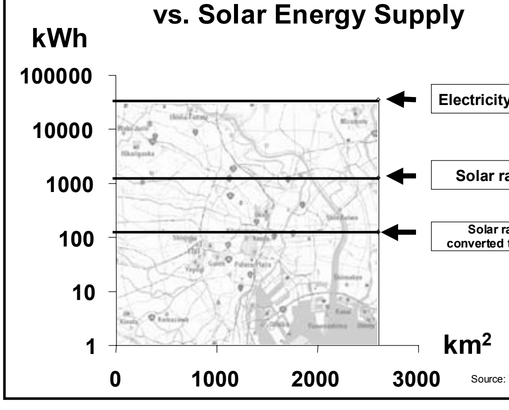
Tokyo – Electricity Demand vs. Solar Energy Supply



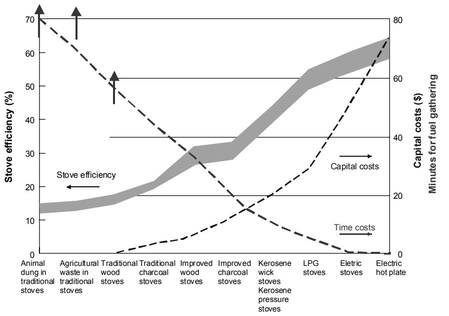
Source: TEPCO & NIES, 2002

Valuation: Multicriteria overall performance

- Efficiency (energy, exergy)
- Productivity (per service rendered, e.g. value added) = Energy Intensity
- Costs (money, time, information)
- Externalities (social, environmental)
- Paramount importance of systems boundaries (“who pays”)

Cooking Stoves

Energy Efficiency and (Capital and Time) Costs



Source: Adapted from OTA, 1992.

Examples of Different Costs of Energy

- Supply costs (producer perspective): $/gal **to** station
- Consumer purchase costs (incl. taxes, DOE perspective): $/gal **from** station
- Direct end-use costs (consumer perspective): purchase & maintenance of car + $/gal
- IRM: producer + consumer costs
- Neglected costs:
  -- inconvenience costs:
  Riding a small, efficient car;
  heating with gas ($$$), not coal ($)
  -- social externalities (accidents)
  -- environmental externalities (pollution)

Implications:

Rules of thumb for economists and policy makers

(very rough orders of magnitude)

At wellhead:	1 $/bbl
Before Prod. Gov.:	3 $/bbl
Upstream (trade):	10 $/bbl
Before Cons. Gov.:	30 $/bbl
Consumer:	>100 $/bbl
Total energy:	>300 $/bbl
Society:	>1000 $/bbl
Total system:	>3000 $/bbl