FIRST- AND SECOND-LAW EFFICIENCIES OF THE GLOBAL AND REGIONAL ENERGY SYSTEMS

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Preface

Improvement of energy efficiencies is one of the most important measures for both reducing energy requirements for growing global population and for mitigating adverse energy-related environmental impacts. IIASA's Environmentally Compatible Energy Strategies Project has been conducting a detailed and comprehensive assessment of specific technological options that can help reconcile the seemingly conflicting objectives of providing adequate energy for development in the world and assuring environmental protection. It is in this context that the authors of the paper have analyzed the current, prevailing energy efficiency in the world and have taken a novel approach to apply the second law of thermodynamics to determine the ultimate efficiency improvement potential. An important conclusion of this analysis is that this potential is truly enormous and should by itself not pose a limit to efficiency improvement for providing energy services from energy sources available to humanity. A more stringent constraint to energy improvement will be time; namely, whether the rates of improvement will be high enough so as to allow for increases in provision of energy services at much higher rates than the increasing primary energy requirements in the world. Historical analysis of the global energy system for the last two centuries shows continuous efficiency improvements at average rates of about one percent per year. In the future, the real challenge will be to increase these efficiency improvement rates. The analysis presented in this paper shows that the theoretical potential to do so is available.

This paper was presented during the 16th Congress of the World Energy Council (WEC) in Tokyo in 1995. This and other presentations by IIASA scientists at the Congress represent an important stage in the collaboration between IIASA and WEC in their attempt to formulate a future vision on the implications of near-term decisions by the world's energy community on long-term energy perspectives.

Peter E. de Jánosi
Director

16th CONGRESS OF THE WORLD ENERGY COUNCIL

Summary

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SUMMARY

This paper presents estimates of the global energy efficiency improvement potential by applying first- and second-law, or exergy, analysis to regional and global energy balances. The investigation is based on the uniform analysis of national and regional energy balances and the aggregation of these balances into the main regions and subsequently into world totals. The procedure involves the assessment of exergy efficiencies at each step of energy conversion, from primary to final and useful exergy. Ideally, the analysis should be extended to actual energy services delivered. Unfortunately, data are scarce and only rough estimates can be given for the last stage of the energy chain. The overall result is that current global useful exergy efficiency is about one-tenth of the theoretical maximum and service efficiency is only a few percent. Whereas conventional energy analysis grossly overestimates the prevailing conversion efficiencies, exergy analysis provides a more appropriate yardstick.

Energy efficiency improvements are considered one of the most effective means of decreasing global energy requirements and related adverse environmental impacts without reducing the quality of energy services delivered. Historical analysis of the energy systems shows continuous efficiency improvements of energy chains of about 1% per year, measured by energy intensity, due to technological, structural, and social changes; it also allows some prospectives into the future. Efficiency improvements of energy supply are mostly technology driven, whereas improvements in energy use depend more on lifestyles.

Original points that the authors wish to stress:

a) Overall primary to useful energy efficiency of the world is less than 30%; exergy (second-law) efficiency is about 10%, and it is only a few percent for the primary to service efficiency.

b) Historical analysis of the energy system shows continuous efficiency improvements averaging about 1% per year.

c) Efficiency improvements of the energy supply are mostly technology-driven; energy end use depends more on lifestyles and may be susceptible to policy tools like demand-side management.

16eme CONGRES DU CONSEIL MONDIAL DE L'ENERGIE

Résumé

RENDEMENT ENERGETIQUE ET EXERGETIQUE DU SYSTEME ENERGETIQUE GLOBAL ET REGIONAL

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RÉSUMÉ

Cet article présente une estimation, fondée sur l'analyse exergétique, des marges d'amélioration de l'efficacité énergétique globale. Ce résultat a pu être obtenu grâce à une analyse cohérente, avant leur aggrégation, des bilans énergétiques par pays ou par région. Le raisonnement requiert une évaluation du rendement exergétique à chaque étape de la conversion énergétique, de l'éxergie primaire jusqu'à l'éxergie finale ou utile. Dans le meilleur des cas, l'analyse serait poussée jusqu'au service énergétique réellement fourni; mais le peu de données n'autorise guère qu'à approximer ce dernier maillon de la chaîne énergétique. On obtient finalement que le rendement exergétique primaire-utile global observé n'est environ qu'un dixième du maximum théorique; quant au rendement primaire au service il n'en représente que quelques points pour cent. Alors qu'une analyse énergétique conventionnelle surestime largement les rendements de conversion, l'analyse exergétique offre une mesure plus satisfaisante.

On peut alors envisager l'amélioration du rendement énergétique comme un des moyens les meilleurs pour parvenir à réduire les besoins en énergie, et donc les impacts sur l'environnement, sans diminution de la qualité des services fournis. Des changements techniques, structurels et sociaux, ont permis au cours de l'histoire une amélioration continue des rendements énergétiques; leur étude autorise à quelques prospectives pour l'avenir. Cette amélioration historique, mesurée en intensité énergétique du PIB, s'élève à environ un pour cent par an. Dans les premiers maillons de la chaîne énergétique (approvisionnement), les améliorations de rendement découlent principalement du progrès technique; les derniers (utilisation finale), en revanche, dépendent davantage du mode de vie.

Les auteurs souhaitent particulièrement souligner quelques points originaux:

a) le rendement global de la conversion d'énergie primaire à l'énergie utile est en-dessous de 30%; mais l'analyse exergétique donne un résultat inférieur à 10%, et qui tombe encore en deçà lorsque l'analyse s'étend à l'approvisionnement des services;
b) l'analyse historique de l'amélioration des rendements indique une baisse de l'intensité énergétique de l'ordre d'un pour cent par an;
c) les améliorations de rendement dans l'approvisionnement d'énergie découlent principalement du progrès technique; l'utilisation finale, en revanche, serait davantage susceptible de gestion par la demande.

FIRST- AND SECOND-LAW EFFICIENCIES OF THE GLOBAL AND REGIONAL ENERGY SYSTEMS

RENDEMENT ENERGETIQUE ET EXERGETIQUE DU SYSTEME ENERGETIQUE REGIONAL ET GLOBAL

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1. Introduction

1. Introduction

Improvement in efficiency at all stages of the energy system is generally considered one of the most effective means of decreasing global energy requirements and related adverse environmental impacts without reducing the quality of energy services delivered. During the last few years, a number of studies have been published on actual and potential energy efficiencies of individual technologies (e.g. Ayres, 1989; Olivier *et al.*, 1983; Rosen, 1992), based on the first or the second law of thermodynamics. To determine the overall global and regional energy efficiencies of the energy system, data on energy conversion and end use are required. Primary energy statistics are available for most of the world regions (WEC, 1993; IEA, 1993c); primary to final energy statistics are available only for the industrialized countries (IEA, 1993b). From these energy statistics, primary to secondary conversion efficiencies (of the transformation sector) and primary to final energy supply efficiencies for the end use (industry, transport, residential and commercial sectors) can be inferred for individual fuels, energy carriers, and the whole energy system. Data on the efficiencies of energy conversion from final to useful energy are more scarce. Relevant investigations have been made by Nakićenović *et al.* (1989) and by Gilli *et al.* (1990) for the Organization for Economic Cooperation and Development (OECD) countries; by Rosen (1992) for Canada; by Schaeffer and Wirtshafter (1992) for Brazil; and by Özdoğan and Arikol (1995) for Turkey. An estimate of global primary to useful efficiency for the late 1980s was made by Nakićenović (1993).

This paper reports the results of a uniform investigation into the energy systems of countries and subregions. These subregions were aggregated into three main economic regions: OECD countries, reforming economies (RC), and developing countries (DC). Results for the main regions and for the world as a whole are presented using base year 1990.

In the following sections, energetic (first law of thermodynamics) and exergetic (second law of thermodynamics) efficiencies are defined. Section 3 contains energy and exergy balances for the three main economic regions and for the world. In Section 4 the main assumptions for developing the balances are described and the resulting efficiencies are presented, discussed, and compared with data from the literature. In Section 5 the potential for further improvement is estimated, and in Section 6 conclusions are drawn.

2. Definition of efficiencies
2. Définition des rendements

Energetic efficiency, or first-law efficiency, is defined as the ratio of energy transferred to the ultimate purpose of the system divided by the actual energy input to the system (not counting "free", e.g. ambient, heat). When the theoretical maximum value of the energetic efficiency is greater than 100%, it is called the coefficient of performance (COP); otherwise, it is called efficiency and is denoted by η.

Heat pumps have COP values that usually are much greater than 100%; furnaces have an efficiency of less than 100%. This is true at least if the energy input of the fuel is measured by the gross calorific value or higher heating value (HHV). If the net calorific value or lower heating value (LHV) - excluding the heat of condensation of the water vapor in the flue gas - is used, and if the flue gas is cooled down to a temperature where sufficient condensation occurs, efficiencies of 100% or even slightly higher are possible in a condensing boiler under favorable circumstances.

Obviously, it is not satisfactory that efficiencies can be below or above 100%. Therefore, the second-law efficiency, or exergetic efficiency, v is defined; its maximum (ideal) value for a process is 100%. Second-law analysis can be based on the entropy or the exergy (available energy) concept. Currently, the exergy concept is often preferred because it is a positive concept: High temperature means high exergy but low entropy. And the division of energy into an exergy (b) and an anergy (a) part is, in principle, easy to handle.

To apply the exergy concept (Thring, 1944; Cambel *et al.*, 1980; ASME 1987, 1988, 1992; Kotas *et al.*, 1987; Moran and Sciubba, 1994), a distinction must be made between closed systems (internal energy, u) and open systems (enthalpy, h). Technical applications usually use open systems.

As far as heat (q) is concerned, exergy (b) and enthalpy (h) are coupled by a quality factor, the Carnot factor v_c, depending on absolute working temperature T and ambient temperature T_0. This follows from the definition of entropy (s), or rather its differential (ds):

$ds = (1/T)dq = (1/T)\ dh$
$db = dh - Tds = dh - (T_o/T)dq = (1 - T_o/T)dh = v_c dh$
$v_c = db/dh = |1 - T_o/T| = |(T - T_o)/T|$

Figure 2-1 shows the quality factor v_c for heat, based on T_o = 294 K (= 21 °C). At ambient temperature, v_c becomes zero. At very high temperatures $v_c = 1 - T_o/T$ approaches 100%. For $T < T_o/2$, v_c becomes greater than 100%. This does not contradict the above statement that v_c of a process is always less than 100%; it only states that heat at very low temperatures contains (and requires for production) large amounts of exergy.

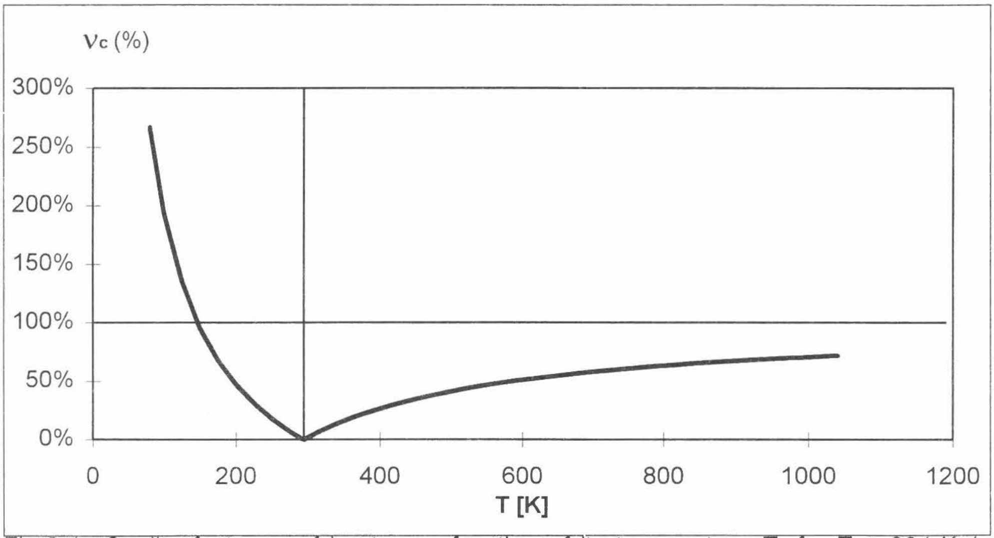

Fig 2-1 Quality factor v_c of heat as a function of its temperature T, for T_o = 294 K (= 21 °C)
Facteur de qualité v_c de la chaleur comme fonction de la température T, pour T_o = 294 K (= 21 °C)

To prepare exergy balances, the chemical exergy of fuels (or the ratio of exergy to energy content) must be determined. This depends on reaction entropy and on the exergies of oxygen and of the flue-gas components. BMHW (1961), Kriese (1971), Baehr (1979, 1992), Szargut *et al.* (1988), Srivastava (1988), and Rosen (1992) give slightly different exergy values for fuels. However, the exergy of solid and liquid fuel is generally near the HHV, whereas that of gases is near the LHV. In Table 2-1, approximate values of the ratios f_c = HHV/LHV, f_x = b/HHV, and $f_e = f_x.f_c$ = b/LHV are given; these are used for the calculations in the following sections.

As mentioned at the beginning of this section, the efficiency of fuel conversion into heat will depend on whether the fuel energy is taken at LHV or HHV. The World Energy Council (WEC, 1988), and the United Nations (UN, 1992), recommend the use of LHV; the International Energy Agency (IEA, 1993a) statistics use the HHV for gas, whereas the IEA (1993b) energy balances are based on the LHV.

Table 2-1 Relation between lower heating value (LHV) and upper heating value (HHV) and exergy (b) for some fuels

Tableau 2-1 Relations entre exergie et valeurs calorifiques basse et haute de quelques combustibles

	f_c = HHV/LHV	f_x = b/HHV	$f_e = f_x \cdot f_c$ = b/LHV
Hard Coal	1.03	1.02	1.05
Brown Coal (LHV = 17 MJ/kg, 19% H_2O, 17% ash)	1.08	1.03	1.11
Wet Brown Coal (LHV = 10 MJ/kg, 54% H_2O, 6% ash)	1.18	1.03	1.22
Brown Coal, Average	1.13	1.03	1.16
Coal, Average (10% Brown Coal)	1.04	1.02	1.06
Crude Oil; Fuel Oil	1.05	0.99	1.04
Natural Gas	1.11	0.93	1.03
Wood (Biomass), Dry (20% H_2O)	1.10	1.03	1.13
Wood (Biomass), Wet (50% H_2O)	1.25	1.03	1.29
Wood (Biomass), Average	1.16	1.03	1.19
Nuclear Fuel	-	1.00	1.00

In Table 2-2, the steps of energy conversion are listed - from primary via secondary and final to useful energy and to energy service. For each step of conversion, the kind of technology, typical technology examples, and the type of efficiency are given. Variables bearing an "x" refer to exergy rather than energy.

Energetic and exergetic efficiencies from primary energy down to useful energy are well defined and, in principle, can be measured. The efficiencies between useful energy and energy service are less well defined; their definition depends on the somewhat loose definition of energy service.

Table 2-2 Conversion steps in energy and exergy end use and services

Tableau 2-2 Etapes de la conversion énergétique et exergétique

Conversion	Technology	Examples	Efficiency
Primary Energy P (Exergy P_x)			
S/P (S_x/P_x)	Fuel conversion, Electricity generation	Refinery, Power station	Energetic and exergetic transformation efficiency (η_t, v_t)
Secondary Energy S (Exergy S_x)			
F/S (F_x/S_x)	Distribution	Grid, Road tanker	Energetic and exergetic distribution efficiency (η_d,v_d)
Final Energy F (Exergy F_x)			
U/F (U_x/F_x)	Final energy conversion (and distribution) technologies	Boiler and heat distribution system (up to radiator), Light bulbs, Vehicle engines	Energetic and exergetic final energy conversion (and distribution) efficiency (η_{fc}, v_{fc})
Useful Energy U (Exergy U_x)			
Z/U (Z_x/U_x)	Energy (exergy) service technologies	Heated space, Passenger-km, Lighted area	Energetic and exergetic service factors or efficiency (f_s)
Energy Service Z (Exergy Z_x)			

3. Regional and global energy and exergy balances
3. Bilans énergétiques et exergétiques régionaux et globaux

For the calculation of energy and exergy balances, the world was disaggregated into the 11 subregions used in the WEC Study Project 5 on Energy Perspectives. The subregions were aggregated into three main regions: OECD countries, reforming economies (RC), and developing countries (DC).

The main results of the investigation are presented as energy and exergy balances for the OECD countries (Tables 3-1 and 3-2) and as energy balance bar charts (Figure 3-1) for the three main regions. World data are obtained by adding up the data for the three main economic regions. The world energy balance is presented in Table 3-3; the world exergy balance is presented in Table 3-4. Table 3-5 gives useful to final energy and exergy efficiencies of the three end-use sectors, industry, transport, and residential/commercial, for the three main regions and for the world. Table 3-5 also shows the quality factor $\boldsymbol{v} = U_x/U$ and the ratio U_x/F. Total primary energy requirement (P) for the world is 8,766 Mtoe (million tonnes of oil equivalent), and total exergy 9,281 Mtoe. Final energy is 6,083 Mtoe, final exergy is 6,313; useful energy is 2,371 Mtoe, and useful exergy is 902 Mtoe.

The investigation is based mainly on the IEA (1993b, 1993c) energy balances leading to final energy. The IEA World Energy Outlook (IEA, 1994), the study of the WEC Commission on Energy for Tomorrow's World (WEC, 1993), and preliminary results of the WEC Study Project 5 (Energy Perspectives) were also considered. However, in the course of the work, it was appropriate to depart from some or all of the references quoted above, and from previous work in general:

- This investigation is carried beyond final energy to useful energy. Final to useful efficiencies were estimated for each individual energy service in different world regions.
- Based on the energy balances, exergy balances were also prepared using the factors from Table 2-1 in the conversion of primary energy of fuels (LHV) to fuel exergy.
- Noncommercial energy (mainly biomass) was taken into account to the extent quoted by WEC (1993) for non-OECD countries.
- Following the practice of IEA, bunkers (marine and international air) have been subtracted from the regional and global balances. Globally they amount to about 118 Mtoe.

The energy balances are given in Mtoe, where 1 Mtoe = 42 PJ (LHV) = 11.67 TWh, as recommended by WEC (1993). The IEA (1993b, 1993c) energy balances use the almost identical value 41.87 PJ = 11.63 TWh. Other energy carriers are converted into Mtoe according to their LHV. Nuclear energy is assessed from the gross electricity generated by means of a plant efficiency of 32%. Hydro energy is assessed according to the gross electricity generated (although an efficiency of 85% to 90% between electricity and the kinetic and potential energy of the water flowing through the turbines might have been more correct). Hydro energy also includes electricity generation from wind, solar, and geothermal energy; renewable fuel comprises biomass and biomass-derived fuel (e.g., biodiesel), but also municipal and other waste, which consists mainly of biomass or biomass products, e.g. paper.

Table 3-1 Energy balance (Mtoe), OECD countries, 1990
Tableau 3-1 Bilan énergétique (Mtoe), OECD, 1990

	Coal	Ren.Fuel	Oil	Gas	Nuclear	Hydro	Electr.	Heat	Total
Domestic Production (D)	908	133	759	688	438	98	-	-	3,024
Trade,Bunkers,Storage (T)	0	13	963	98	-	-	1	-	1,074
Primary Requirement (P)	908	145	1,723	786	438	98	1	-	4,098
Fuel Conversion (C)	-23	0	-26	-17	-	-	-6	0	-72
to Electricity and CHP (E)	-664	-34	-141	-164	-438	-98	-	-	-1,538
to District Heat (H)	-6	-2	-1	-2	-	-	-	-	-10
Electr. & Heat from CHP	(248)	(13)	(58)	(68)	(140)	(98)	609	15	624
District Heat	(5)	(1)	(1)	(1)	-	-	-	8	8
Secondary (S)	215	110	1,555	604	-	-	604	24	3,111
Own Use, Distr.Losses (L)	-12	0	-52	-70	-	-	-90	-7	-230
Final (F)	203	110	1,503	534	-	-	514	17	2,881
Non-Energetic (N)	2	-	240	14	-	-	-	-	256
Energetic Final (F')	201	110	1,264	520	-	-	514	17	2,626
Useful (U)	123	61	358	326	-	-	389	15	1,272
$S/(P-E-H)=S/P'$ (%)	90.2	99.7	98.4	97.3	-	-	40.5		75.9
F/S (%)	94.6	100.0	96.7	88.4	-	-	84.6		92.6
U/F' (%)	61.0	55.8	28.3	62.8	-	-	75.6		48.4
$(S/P')(F/S) = F/P'$ (%)	85.3	99.6	95.1	86.0	-	-	34.3		70.3
$(F/P')(U/F') = U/P''$ (%)	52.1	55.6	26.9	54.0	-	-	25.9		34.1

Table 3-2 Exergy balance (Mtoe), OECD countries, 1990
Tableau 3-2 Bilan exergétique (Mtoe), OECD, 1990

	Coal	Ren.Fuel	Oil	Gas	Nuclear	Hydro	Electr.	Heat	Total
Domestic Production (D_x)	962	158	790	709	438	98	-	-	3,155
Trade,Bunkers,Storage (T_x)	0	15	1,002	101	-	-	1	-	1,118
Primary Requirement (P_x)	962	173	1,791	810	438	98	1	-	4,273
Fuel Conversion (C_x)	-25	0	-27	-17	-	-	-6	0	-75
to Electricity and CHP (E_x)	-704	-40	-146	-168	-438	-98	-	-	-1,595
to District Heat (H_x)	-6	-2	-1	-2	-	-	-	-	-11
Electr. & Heat from CHP	-	-	-	-	-	-	609	4	613
District Heat	-	-	-	-	-	-	-	2	2
Secondary (S_x)	228	131	1,617	622	-	-	604	6	3,207
Own Use, Distr.Losses (L_x)	-12	0	-54	-72	-	-	-90	-2	-229
Final (F_x)	215	131	1,563	550	-	-	514	4	2,978
Non-Energetic (N_x)	2	-	249	15	-	-	-	-	266
Exergetic Final (F_x')	213	131	1,314	536	-	-	514	4	2,712
Useful (U_x)	36	12	187	72	-	-	166	2	475
$S_x/(S_x+C_x)=S_x/P_x'$ (%)	90.2	99.7	98.4	97.3	-	-	38.0		75.1
F_x/S_x (%)	94.6	100.0	96.7	88.4	-	-	85.0		92.8
U_x/F_x' (%)	16.7	9.3	14.2	13.5	-	-	32.2		17.5
$(S_x/P_x')(F_x/S_x) = F_x/P_x'$ (%)	85.3	99.6	95.1	86.0	-	-	32.3		69.7
$(F_x/P_x')(U_x/F_x') = U_x/P_x''$ (%)	14.2	9.2	13.5	11.6	-	-	10.4		12.2

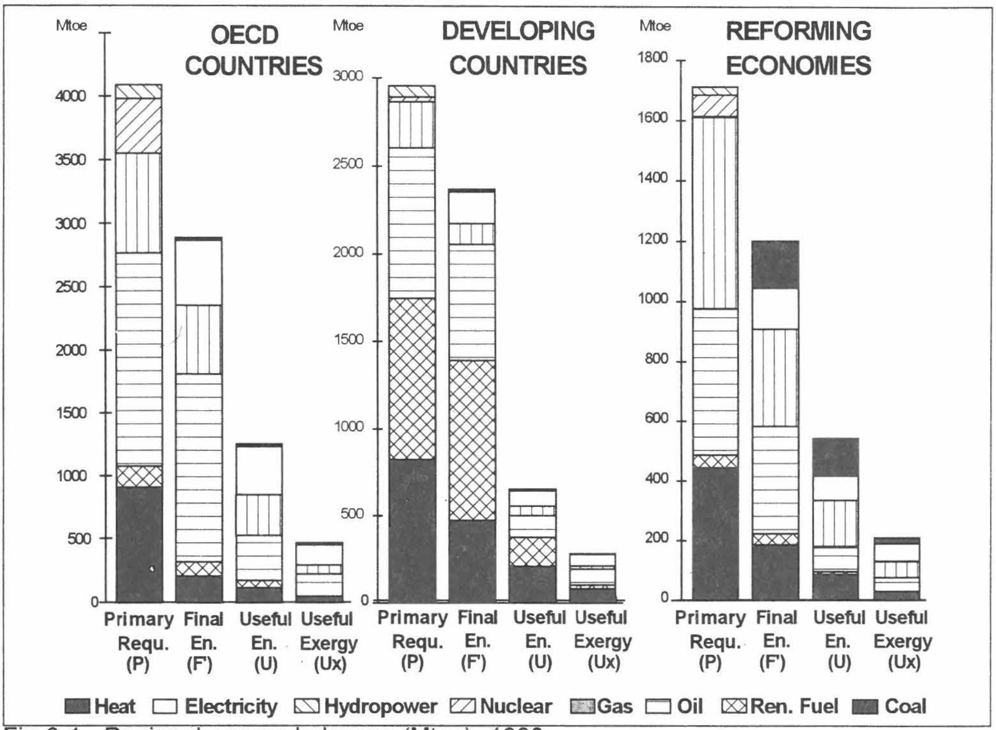

Fig 3-1 Regional energy balances (Mtoe), 1990
Bilans énergétique régionaux (Mtoe), 1990

For each energy carrier, the energy chain leads from domestic (primary energy) production (D) via international trade, bunkers, and storage (T) to primary energy requirement (P), and further via fuel conversion (refineries, gas works, etc., C), input for electricity generation (E, including combined heat and power, CHP), and district heat (H) to secondary energy (S). By subtracting own use (of the energy transformation sector) and distribution losses (L), gross final energy (F) is obtained. Subtracting non-energetic use (N, including feedstocks) leads to (net) final energy (F'), followed by useful energy (U). The following should be noted:

- For the regional balances, imported energy is measured at the respective border. Upstream losses in fuel production and long-distance transport (WEC, 1988) are counted in the region concerned (and are, therefore, not listed in Table 2-2).

- Bunkers include marine and international aviation fuel; they are deducted in T when proceeding from D to P, and thus are not part of F and U.

- Total electrical output of power and combined heat and power (CHP) plants is shown in the Electricity column. The distinction according to energy source is shown in the respective column in brackets. Following the IEA procedure, heat output of CHP plants and of district heating plants without electricity generation is shown in the Heat column. The Electricity and CHP lines include all electricity from industrial cogeneration plants, but only traded heat; industrial process heat from CHP plants that is used within the enterprise is not shown in line CHP; the corresponding fuel input is part of industrial final energy.

Table 3-3 Energy balance (Mtoe), world, 1990
Tableau 3-3 Bilan énergétique (Mtoe), monde, 1990

	Coal	Ren. Fuel	Oil	Gas	Nuclear	Hydro	Electr.	Heat	Total
Domestic Production (D)	2,197	1,103	3,215	1,711	541	188	-	-	8,954
Trade,Bunkers,Storage (T)	-20	9	-151	-26	-	-	0	-	-188
Primary Requirement (P)	2,176	1,112	3,064	1,685	541	188	0	-	8,766
Fuel Conversion (C)	-68	0	-112	-12	-	-	-18	-14	-223
to Electricity and CHP (E)	-1,157	-45	-340	-396	-541	-188	-	-	-2,666
to District Heat (H)	-45	-2	-2	-91	-	-	-	-	-140
Electr. & Heat from CHP	(440)	(17)	(138)	(168)	(173)	(188)	1,019	103	2,245
District Heat	(33)	(1)	(2)	(72)	-	-	-	108	108
Secondary (S)	907	1,065	2,610	1,186	-	-	1,002	198	6,967
Own Use, Distr.Losses (L)	-44	-2	-79	-211	-	-	-170	-11	-518
Final (F)	863	1,063	2,531	975	-	-	831	187	6,450
Non-Energetic (N)	2	-	336	29	-	-	-	-	367
Energetic Final (F')	861	1,063	2,195	946	-	-	831	187	6,083
Useful (U)	370	207	544	533	-	-	558	160	2,371
S/(P-E-H)=S/P' (%)	93.0	100.0	95.9	99.0	-	-	42.7		79.5
F/S (%)	95.2	99.8	97.0	82.2	-	-	84.9		92.6
U/F' (%)	43.0	19.4	24.8	56.4	-	-	67.1		39.0
(S/P')(F/S) = F/P' (%)	88.5	99.8	93.0	81.4	-	-	36.3		73.6
(F/P')(U/F') = U/P" (%)	38.0	19.4	23.0	45.9	-	-	24.4		28.7

Table 3-4 Exergy balance (Mtoe), world, 1990
Tableau 3-4 Bilan exergétique (Mtoe), monde, 1990

	Coal	Ren. Fuel	Oil	Gas	Nuclear	Hydro	Electr.	Heat	Total
Domestic Production (D_x)	2,329	1,313	3,343	1,762	541	188	-	-	9,476
Trade,Bunkers,Storage (T_x)	-22	11	-157	-27	-	-	0	-	-194
Primary Requirement (P_x)	2,307	1,324	3,186	1,735	541	188	0	-	9,281
Fuel Conversion (C_x)	-72	-1	-116	-12	-	-	-18	-3	-222
to Electricity and CHP (E_x)	-1,226	-53	-353	-408	-541	-188	-	-	-2,770
to District Heat (H_x)	-48	-2	-2	-94	-	-	-	-	-146
Electr. & Heat from CHP	-	-	-	-	-	-	1,019	26	1,045
District Heat	-	-	-	-	-	-	-	27	27
Secondary (S_x)	961	1,268	2,715	1,221	-	-	1,002	49	7,216
Own Use, Distr.Losses (L_x)	-47	-2	-83	-217	-	-	-170	-3	-522
Final (F_x)	915	1,265	2,632	1,004	-	-	831	47	6,694
Non-Energetic (N_x)	2	-	349	30	-	-	-	-	381
Exergetic Final (F_x')	912	1,265	2,283	974	-	-	831	47	6,313
Useful (U_x)	107	34	314	133	-	-	285	29	902
$S_x/(S_x+C_x)=S_x/P_x'$ (%)	93.0	100.0	95.9	99.0	-	-	36.1		77.7
F_x/S_x (%)	95.2	99.8	97.0	82.2	-	-	83.5		92.8
U_x/F_x' (%)	11.7	2.7	13.8	13.6	-	-	34.3		14.3
$(S_x/P_x')(F_x/S_x) = F_x/P_x'$ (%)	88.5	99.8	93.0	81.4	-	-	30.1		72.1
$(F_x/P_x')(U_x/F_x') = U_x/P_x''$ (%)	10.4	2.7	12.8	11.1	-	-	10.3		10.3

- Distribution losses for grid energy (electricity, district heat, and gas) are the differences between secondary and final energy. For non-grid energy (solid and liquid fuels), distribution losses are not shown; they are part of the end-use sector transport (e.g. car tanker). Own use in the transformation sector, as well as the requirements for pumped storage, are included in the distribution losses.

Table 3-5 Energy and exergy use (Mtoe) in the main regions and in the world, 1990
Tableau 3-5 Energie utile et exergie (Mtoe) par secteurs et par région, 1990

		OECD	RCs	DCs	World
Residential/Commercial					
Final Energy	F'	918.10	432.96	1,249.61	2,600.67
Useful Energy	U	562.39	173.59	212.58	948.56
Useful Exergy	U_x	64.14	24.97	45.10	134.21
$v_c = U_x/U$	(%)	11.40	14.38	21.22	14.15
U_x/F'	(%)	6.99	5.77	3.61	5.16
Industry					
Final Energy	F'	799.66	551.67	676.27	2,027.60
Useful Energy	U	556.30	318.01	315.02	1,189.33
Useful Exergy	U_x	265.57	136.11	149.17	550.85
$v_c = U_x/U$	(%)	47.74	42.80	47.35	46.32
U_x/F'	(%)	33.21	24.67	22.06	27.17
Transport					
Final Energy	F'	907.75	166.96	380.05	1,454.77
Useful Energy	U	153.36	31.27	48.42	233.06
Useful Exergy	U_x	144.88	25.75	46.51	217.14
$v_c = U_x/U$	(%)	94.47	82.34	96.05	93.17
U_x/F'	(%)	15.96	15.42	12.24	14.93
Total					
Final Energy	F'	2,625.51	1,151.59	2,305.94	6,083.04
Useful Energy	U	1,272.05	522.87	576.03	2,370.95
Useful Exergy	U_x	474.59	186.84	240.78	902.21
$v_c = U_x/U$	(%)	37.31	35.73	41.80	38.05
U_x/F'	(%)	18.08	16.22	10.44	14.83

- The character of the energy changes between final energy (F) and useful energy (U) from energy carriers to energy requirements (such as heat, mechanical energy, and light) generated from the energy carrier.

- No estimates were made concerning energy services (Z in Table 2-2) because there is no energy conversion between U and Z; rather, the service factor f_s represents the possible reduction of useful energy demand, and therefore depends on the definition of what is technically or economically possible. For instance, for a real "zero heating energy house", f_s for any heating system is zero by definition.

The main differences between the exergy balances and the energy balances are:

- Primary exergy of fuels is different from primary energy by the factor f_e, given in Table 2-1.

- For electricity, $f_e = 1$, i.e. exergy is equal to energy. Therefore, the exergetic efficiency of power plants becomes $v = \eta/f$, where η is the energetic efficiency.

- Heat is the only energy carrier whose exergy is lower than its (LHV) energy. For a weighted mean supply temperature of 100°C, and $t_o = 5°C$, f_e becomes 0.25.

4. Efficiencies of energy supply and use
4. Rendement énergétique final et rendement des appareils

In the lower parts of Tables 3-1 to 3-4, a number of efficiencies for each energy carrier are calculated.

To properly apply efficiencies, it is necessary to account for energy use that has nothing to do with the energy carrier itself: one is non-energetic use, the other is input to electricity, CHP, and district heat production. The energetic use of an energy carrier bears the symbol "’". For instance, in Table 3-3 the world primary requirement of oil is P = 3,064 Mtoe, secondary energy is S = 2,610 Mtoe, the total final use is F = 2,531 Mtoe, the energetic final use is F’ = 2,195 Mtoe, and useful energy is U = 544 Mtoe. The efficiency η_t = S/P’= 2,610/2,722 = 0.959, where P’ = P - E - H = 3,064 - 340 - 2 = 2,722. Further, F/S = 2,531/2,610 = 0.97; F/P’ = 0.93; U/F’ = 544/2,195 = 0.248. Finally, (F/P’)(U/F’) = (U/P’)(F/F’) = U/P" = 5,785/2,362 = 0.23, where P" = P’(F’/F) = 2,722(0.87) = 2,362 Mtoe.

The following efficiencies apply to energy carriers and to the energy system as a whole (Total):

- S/P : transformation efficiency (η_t, v_t)
- F/S : distribution efficiency (η_d, v_d)
- F’/F : share of total final energy used for energetic purposes (η_e, v_e)
- U/F : final energy conversion efficiency (η_{fc}, v_{fc})

Furthermore, the following combined efficiencies are assessed in Tables 3-1 to 3-4:

- F’/P’ : primary to final efficiency ("supply efficiency", $\eta_f = \eta_t \cdot \eta_d$, $v_f = v_t v_d$)
- U/P" : primary to useful efficiency ("overall efficiency", $\eta_u = \eta_f \cdot \eta_{fc}$, $v_u = v_f \cdot v_{fc}$)

Note that, for a given fuel, the efficiencies after the transformation efficiency apply only to the portion (F) on the direct chain of fuel use, not to the portion that is converted to other energy forms such as electricity or heat (E, H). Regarding the conversion steps in the energy balances presented in Section 3, it should be noted that the electricity and heat generation efficiency η_t represents the ratio of electricity and heat output to fuel input.

To obtain useful energy for each end-use sector, the final energy was disaggregated into shares (final energy inputs) for individual energy services, and the final energy conversion efficiencies (η_{fc}, v_{fc}) were applied as a weighted average of each energy carrier for the various conversion technologies used in a region. Examples of ranges and average values of final energy conversion efficiencies U/F = η_{fc} and $U_x/F_x = v_{fc}$ are shown in Figure 4-1. The efficiency ranges shown in Figure 4-1 are an average of all energy carriers. The white bars are energetic conversion efficiencies, the dark bars are exergetic conversion efficiencies. Data were taken mainly from Reistad (1975), Olivier *et al.* (1983), Ayres (1989), EUROSTAT (1988), Nakićenović *et al.* (1989), Gilli *et al.* (1990), Schipper and Howarth (1990), Schaeffer and Wirtshafter (1992), Rosen (1992), and Smil (1993).

Obviously, the shares of final energy input and the conversion efficiencies to be applied to these shares differ greatly among the 11 subregions. In cases where data were unavailable, estimates were used based on interpolation of known values for other regions according to the logarithm of per capita purchasing power parity in 1990. In some cases, subregional data were based on data for several countries of the subregion.

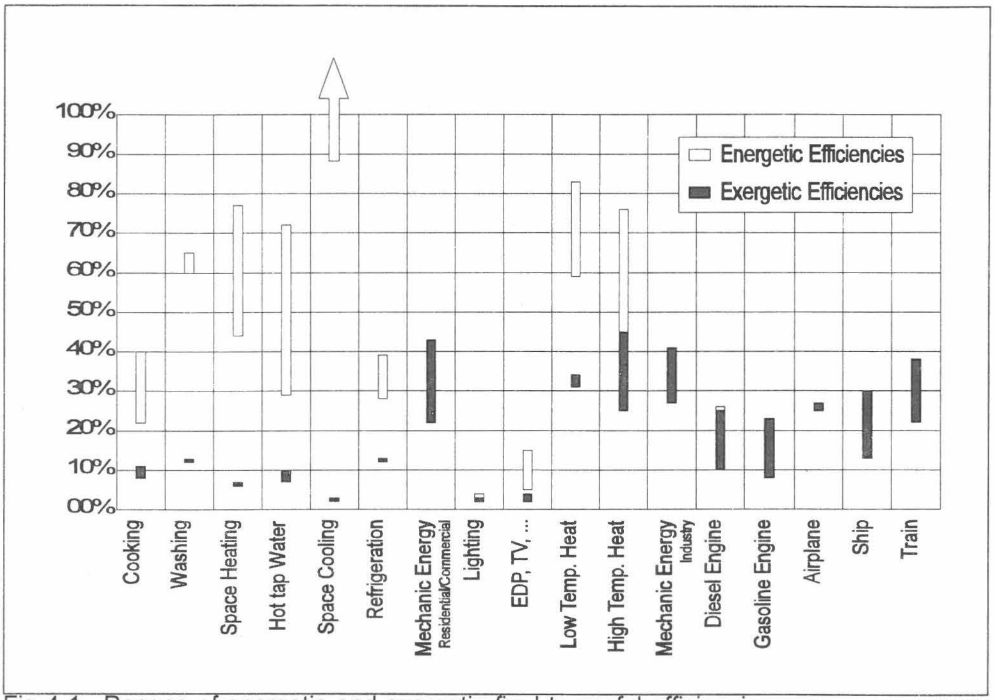

Fig 4-1 Ranges of energetic and exergetic final to useful efficiencies
Niveaux des rendements énergétiques et exergétiques finaux

The exergy of heat is given by the quality factor v_c (Figure 2-1), which depends on temperatures. Values of temperature and corresponding v values of useful energy as used in the exergy balances are listed in Table 4-1. This table also contains quality factors for non-thermal uses, such as mechanical energy and lighting. Light is assumed to have a v_c value of 90%, approximately equivalent to that of direct solar radiation; v_c for other specific applications of electricity, such as electronic data processing (EDP), television (TV), etc., is assumed to be 30%; energy for transportation is assumed to consist of 99% exergy, accounting for non-mechanical auxiliaries such as air conditioning.

The chain of efficiencies as listed at the ends of Tables 3-3 and 3-4 and defined at the beginning of Section 4 is depicted in Figure 4-2 showing the efficiencies of the individual energy carriers for the world, starting with P = 100%, up to useful energy and including useful exergy. Figure 4-2 shows that the useful energy of coal is relatively high (due to industrial process heat). The useful energy of biomass is very low (due to low-efficiency cooking and heating); its exergetic efficiency is even lower. The low energetic efficiency of oil is due to its use in cars; its relatively high exergetic efficiency is due to v_c = 100% for mechanical energy. Gas has the highest energetic efficiency but has low exergetic efficiency (due to space heating). The Electricity and Heat column represents the indirect chain (via power plant) of primary energy use. In this case, the useful exergy is slightly above average. If useful exergy is related to electricity, the efficiency is more than twice the average.

Table 4-1 Exergetic quality factors of useful energy (typical values)
Tableau 4-1 Rendement exergétique, énergie utile (valeurs type)

		t_o (°C)	t (°C)	ΔT $= t - t_o$ (K)	T = t+273 (K)	v = ΔT/T (%)
Space Heating		+1	21	20	294	6.8
Hot Tap Water		+12	45	33	318	10.4
Cooking		+21	165	144	438	32.9
Washer; Dishwasher		+12	85	73	358	20.4
Air Conditioning		+28	+21	7	294	2.4
Refrigerator/Freezer		+21	-20	41	253	16.2
Lighting		-	-	-	-	90.0
EDV, TV, etc.		-	-	-	-	30.0
Industrial Process Heat:	Fuel	+12	110	98	383	25.6
	Electricity	+12	135	123	408	30.2
High Temperature Heat		+12	600	588	873	67.4
Mechanical Energy		-	-	-	-	100.0
Transport		-	-	-	-	99.0

The disaggregation of the world data into the three main regions is shown in Figure 3-1 and in Table 3-5; the latter also includes a separation of the data into the three sectors. It should be noted that worldwide the shares of total final energy of residential/commercial, industry, and transport sectors are 43%, 33%, and 24% respectively, whereas the percentages in the OECD countries are 35%, 30%, and 35%, respectively. In the RCs industrial use is above 50%; in the DCs the residential/commercial sector requires 54%.

Overall, the primary to final energy conversion processes are quite efficient: the global average is about 74% (Table 3-3); efficiency is highest in the DCs at about 80% and is lowest in RCs at 70%. It is perhaps counterintuitive that the DCs should have a higher efficiency than the RCs, although many individual energy chains such as electricity are delivered with much lower efficiencies. This is because the shares of the energy carriers with lower primary to final efficiency at present, such as electricity, are much lower; the share of biomass with high F/P efficiency is higher in the DCs than in the former Soviet Union and Eastern Europe.

In comparison, the final to useful energy conversion efficiency is very low: 39% at the global level, only 25% in the DCs, 45% in the RCs, and 48% in the OECD countries. In general, natural gas and electricity have the highest end-use efficiencies and the lowest primary to final conversion rates. The lowest end-use efficiencies can be observed for biomass, with 19% at the global level and only 15% in the RCs and DCs.

In the residential/commercial sector, $v = U_x/U$ is highest in the DCs (21%), and is lowest in OECD countries (11%), whereas U_x/F is highest in OECD countries, and is lowest in the DCs (Table 3-5). This is explained by a large share of heating in OECD countries, and a high share of low-efficency cooking in DCs. Exergetic efficiencies (v) in the industrial sector are similar in the three main regions; energetic efficiencies are highest in OECD countries and are lowest in DCs. Transport efficiencies are also rather similar, as was to be expected.

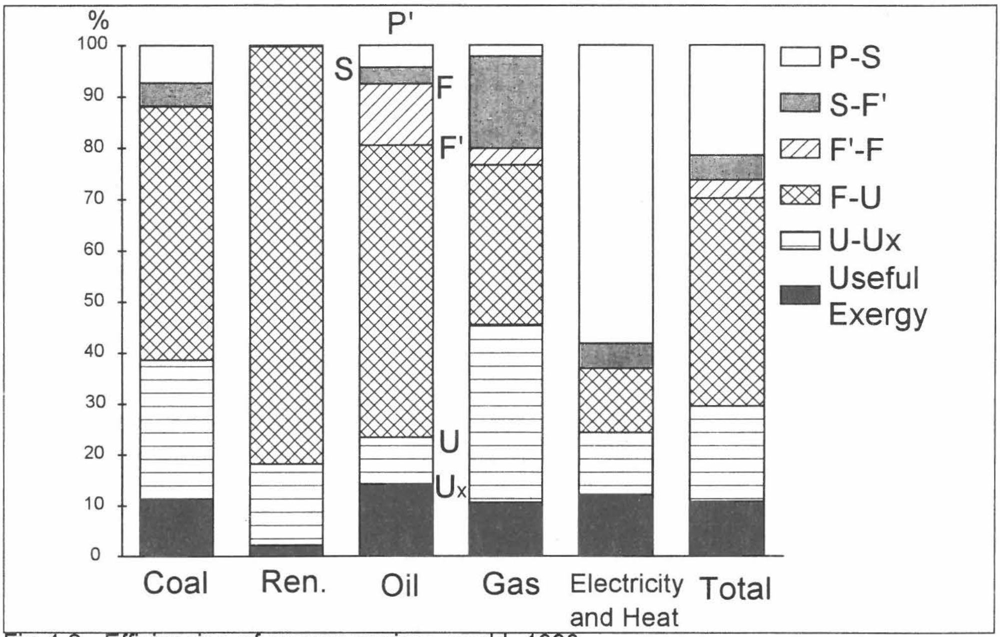

Fig 4-2 Efficiencies of energy carriers, world, 1990
Rendements des transports d'energie, monde, 1990

The resulting overall primary to useful energy efficiency is 29% at the global level; it is lowest in the DCs (20%), is 32% in the RCs, and 34% in the OECD countries. The relatively high value in the RCs is a surprising result. Generally, the energy systems of these economies are rather inefficient, especially when compared with the standards prevailing in the market economies of the OECD countries. All individual primary to useful energy chains are more efficient in the market economies than in the RCs. The reason for the high overall aggregate efficiency in the RCs is the large share of gas and district heat from CHP. The overall exergetic efficiency is 10% globally (Table 3-4), compared with 12% in the OECD countries, 11% in the RCs, and 8% in the DCs.

The most important overall result is that energy end use is the least efficient part of all energy systems, and it is in this area that improvements would bring the greatest benefits.

Overall efficiency of the global energy system is low; it is even lower if exergetic (second law) efficiencies are used.

Efficiency improvements in the initial stages of energy conversion are mostly technology driven, whereas improvements in the last stages of energy end use depend more on lifestyles and individual human behavior and may be less susceptible to policy tools such as demand-side management.

Compared with primary to final efficiencies, final to useful energy and exergy efficiencies are rather low. In particular, the relatively low efficiency in exergetic terms calls into question the overall effectiveness of current energy use. This result indicates that, all too often, energy forms with high-quality factors are applied to provide low-quality service. Nevertheless, most of the primary to useful conversion processes are quite efficient compared with lavish consumption of useful energy to provide services. They are the least efficient link in the efficiency of the whole energy system. Examples include inadequate thermal insulation, temperature "control" by opening windows, low occupancy of automobiles, and lighting of empty rooms. Despite the obvious difficulties in determining the service efficiencies due to a genuine lack of data, a number of estimates indicate that the overall primary to service exergy efficiency is only a few percentage points of the theoretical maximum. This is based on aggregate useful to service global efficiency of about 40% (Nakićenović *et al.* 1989; Gilli *et al.* 1990). This result shows that the theoretical efficiency improvement potential might be as great as a 20-fold increase. Thus, the efficiency improvement potential can be considered a natural potential available to humanity much as are other natural resources, such as fossil energy.

As far as is known, there is no comparable study available covering the whole world. There is one study on energetic overall efficiency for the European Union (EUROSTAT, 1988), and there are several studies on energetic and/or exergetic efficiencies of individual countries, partly up to the energy services. For instance, Olivier *et al.* (1983) give a detailed breakdown of final energy according to energy and tasks performed, as well as the energetic efficiencies of the transformation for useful exergy and energy services in Great Britain. Ayres (1989) gives an overall efficiency of energy use in the USA of 2.5%, which includes the energy service factor. Wall (1990), in his study on the Japanese energy system (including, e.g., food and materials such as paper and steel), arrives at an exergetic primary to useful efficiency of 3.8/18 = 21%; and Wall *et al.* (1994) estimate the total exergy and material resources in Italy to be about 15%, with an even lower efficiency of energy use alone. Schaeffer and Wirtshafter (1992), in their study on Brazil, list a large number of individual efficiencies but distinguish only between electrical and nonelectrical (all fuels) final energy; their energetic primary to useful efficiency is 32.4%, their exergetic efficiency is 22.8%. The comprehensive data of Smil (1993) for the rural sector of The People's Republic of China show a high share of fuel input for low- and medium-temperature thermal uses. This leads to a low overall exergetic efficiency.

Rosen (1992), in his paper on energy efficiency in Canada, calculated the energy and exergy flow of electricity and nonelectricity (all fuels). His exergetic efficiency U_x/P is 24% for the whole system and 14% for the residential/commercial sector, which is much higher than the values in Table 3-5. The main reason for this difference is the different v values of space heating energy (v = 6.8% according to Table 4-1, which is related to room temperature 21 °C; v = 17.1% according to Rosen, which is related to a supply temperature of 55 °C). Also, his transport efficiency is somewhat higher.

5. Potential for Improvement
5. Potentiels d'amélioration

As mentioned above, the efficiency of the provision of services is only a few percentage points in industrialized countries. Figures from the RCs and DCs would certainly be substantially lower. This indicates the large theoretical potential for efficiency improvements by a factor of between 10 and 20! Realization of this potential will depend on the implementation of many technological options and organizational innovations. It represents a theoretical potential that is not likely to be exploited until well into the next century.

Unfortunately, there are a number of barriers that may substantially delay or inhibit the achievement of efficiency potential in the near future. One is the cost of these measures and the associated capital requirements. The other class of barriers is related to the inherently long process of innovation diffusion and technology transfer. The introduction of new energy technologies takes anywhere from 10 years for many end-use devices to 50 years in the case of infrastructural investments. Thus the vintage structure of the capital stock and its replacement dynamics determine the likely rates of future efficiency improvements. For example, the replacement of vehicles and rolling stock took between 10 and 20 years in most countries. At the other extreme, the replacement of housing stock is a much slower process, lasting many decades and in some cases even centuries. The realization of some of the efficiency improvement potentials will therefore need to be associated with retrofitting some of the older vintages, which may not be replaced in the near future. In most industrialized countries almost 80% of the capital stock is replaced over a period of 20 years; this means that substantial efficiency gains could be achieved over the next two decades in most energy end uses (Nakićenović, 1993).

Another barrier, of course, is the nature of our economic system and the way optimization procedures are applied. Thermoeconomics, exergoeconomics, and second-law costing are some tools recently developed to deal with this matter (Groscurth and Kümmel, 1989; Valero *et al.*, 1992; Tsatsaronis, 1994).

Technological change has been and will continue to be one of the most powerful determinants in reducing the energy requirements and improving the efficiency of many human activities. Reductions in specific energy needs have been an important feature of the evolution of energy-use patterns over the last two centuries. A historical analysis of energy systems indicates that technological and structural change have resulted in a reduction of specific energy requirements per unit of economic activity. Figure 5-1 (Grübler, 1991) shows the evolution of energy intensity expressed as energy consumption divided by gross domestic product (GDP, in MJ/US$1980) for a number of countries. Today, many of the OECD countries have comparatively low energy intensity compared with the former Soviet Union (FSU) and the two developing regions shown in the figure, centrally planned Asia (CPA) and South Asia (SAS). For the RCs and DCs, GDP is expressed in both market exchange rates (MEXR) and in terms of per capita purchasing power parity (PPP).

The figure shows that these regions have energy intensities today that are comparable with those prevailing in the OECD countries 50 to 100 years ago. During the last century, energy intensity has decreased in the OECD countries shown, typically at about 1% per year. A part of the reduction in the energy intensity during the early phases of industrialization is due to the replacement of noncommercial, and often unsustainable and inefficient, energy use by commercial energy sources. These and even higher rates of energy efficiency improvement might be possible in the developing parts of the world as similar replacement occurs. At the historical long-term rate of energy intensity improvement of about 1% per year, it would take more than 70 years to reduce the average energy intensity by one-half. Using this analogy, it could take almost half of the next century before our postulated energy efficiency improvements could be realized. In any case, the time required to double the efficiency of an energy system and energy end uses might be somewhere between 30 and 40 years, if we assume that the relatively high improvement rates that have prevailed since the mid-1970s could be sustained.

The development of second-law (exergetic) efficiency in three technologies is shown in Figure 5-2 (Marchetti, 1981). The historical evolution of efficiency is given by reporting the efficiency of the best commercial device at a given time as a fraction (η) of the maximum possible thermodynamical efficiency. This efficiency η is shown as a ratio of $\eta/(1 - \eta)$, e.g., efficiency over inefficiency, together with a logistic trend. Three efficiency

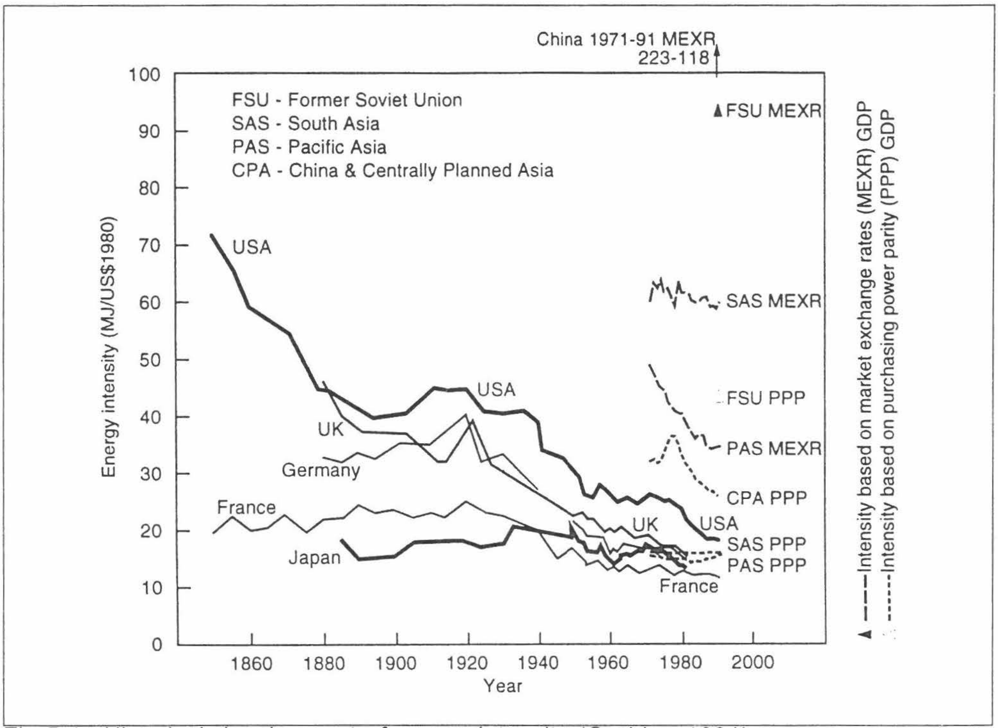

Fig 5-1 Historical development of energy intensity (Grübler, 1991)
Evolution de l'intensité énergétique (Grübler, 1991)

improvement examples are given: prime movers, lighting, and ammonia production. The efficiency of prime movers (in the case of electricity generation approximately equal to power plant efficiency) has been improving from about 1% for the first Newcomen engines to about 50% during the last 300 years. The simple steam-cycle power plant efficiency today has reached about 42% in exergetic terms (45% in energetic terms, based on LHV), even with coal, and may soon approach 50% using new materials and the ultra-supercritical steam cycle. The efficiency of the combined (gas and steam) cycle, using natural gas or light fuel oil, today has reached about 56% in exergetic terms (58% in energetic terms, based on LHV). The increase of fuel efficiency in transport is of similar magnitude (Grübler *et al.*, 1992). The efficiency development of lighting and of ammonia production was even more rapid (Figure 5-2).

Similar technical opportunities to increase energy efficiency exist in most energy end uses. The question is whether some of them will be offset by changes in behavior and lifestyle. Diffusion of new technologies can be a long process, perhaps lasting long enough to allow fundamental increase in demand for energy services, again potentially offsetting some of the gains achieved through improved energy efficiency.

Apart from individual technologies, systems integration using energy cascading is a means of increasing the efficiency of the whole energy system (Kashiwagi, 1992). Cogeneration and multiple use of industrial heat are two well-known examples.

Regarding final energy, in many countries space heating, besides transport, is the main energy requirement. The exergetic quality factor of space heat, according to Table

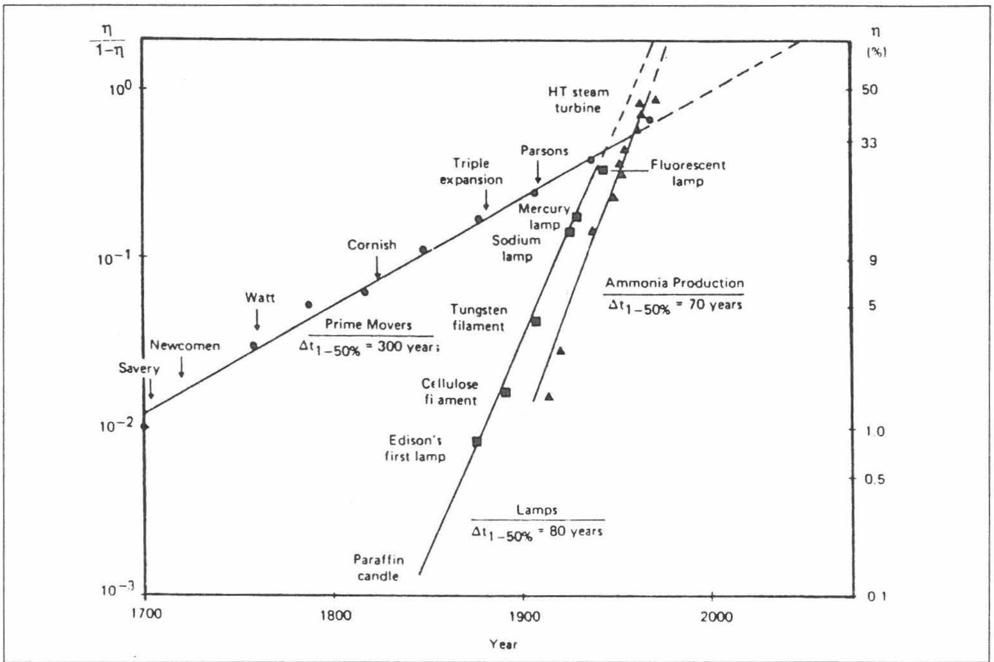

Fig 5-2 Historical development of efficiencies: prime mover, lighting, ammonia production (Marchetti, 1981)
Evolution des rendements: moteurs, éclairage, production d'ammoniaque (Marchetti, 1981)

4-1, is $v = 6.8\%$. The exergetic efficiency v_{fc} of the space heating process is different: e.g, for a gas-fired heating boiler $v_{fc} = \eta_{boiler} v/f = (0.9)(0.068)/1.03 = 0.06$. Using an electrically driven heat pump with a coefficient of performance COP = 3, $v_{fc} = (3)(0.068)/1.0 = 0.21$. Even if the exergy loss of power generation using natural gas and of distribution are accounted for, the heat pump requires less primary energy. However, it should be remembered that with the heating boiler there is almost no possibility of further efficiency improvement, whereas with the energy chain of the heat pump there is: COPs of more than 4 have been reached by ground-coupled heat pumps; further increases are possible. Also, efficiencies of gas-fired power plants will increase further.

6. Conclusions
6. Conclusion

This paper presents estimates of the global energy efficiency improvement potential by applying first- and second-law, or exergy, analysis to regional and resulting global energy balances. The investigation is based on the uniform analysis of national and subregional energy and exergy balances and the aggregation of these balances into the main regions and subsequently into world balances. The procedure involves the assessment of exergy efficiency at each step of energy conversion, from primary to final and useful exergy. Ideally, the analysis should be extended to actual energy services delivered. Unfortunately, data are scarce and only rough estimates can be made for the last stage of the energy chain. The overall result is that current global exergy efficiency is only a few percentage points of the theoretical maximum, compared with more than 20%

efficiency of primary to useful energy conversion by conventional analysis. Thus, conventional energy analysis grossly overestimates the prevailing conversion efficiencies, whereas exergy analysis provides a more appropriate yardstick. This is especially useful for the assessment of energy resources or the environmental limitations of future energy use.

Energy production and conversion is not an end in itself. The complex processes in the energy supply system serve to provide energy services. Therefore, total primary energy requirements are a function of the energy conversion efficiencies and the structure of the energy system for a given pattern of energy services. The analysis of the global primary to useful energy conversion indicates that the overall efficiency is about 30%, and the overall efficiency measured in exergetic terms is about 10%. Because the overall exergy efficiency is a yardstick for the efficiency improvement potential compared to the thermodynamic maximum, the theoretical limit is tenfold higher given the structure of current useful energy demands. The greatest potential for efficiency improvement is the end use, which also has the lowest exergy efficiency. Primary to final exergy efficiency is about 70% worldwide, final to useful exergy is about 15%. Our analysis shows that the final to useful exergy efficiencies are lowest in the residential/commercial sector due to a large share of low-temperature thermal applications. The theoretical efficiency improvement potentials of primary exergy to delivery of services can range up to a factor of 20. Therefore, our analysis identifies large efficiency improvement potentials anywhere in the range of a 10- to 20-fold increase.

In the past, energy efficiency improvements have been largely offset by growth in the demand for energy services. Global economic activities have increased at about 3% per year during this century; primary energy consumption increased about 2% per year during the same period. This indicates that, on average, energy intensity decreased about 1% per year. At this rate, it would take 70 years to double the current global exergy efficiency from 10% to 20%. All of these improvements would not be translated into reductions of primary energy requirements. Instead, efficiency improvement, even if it were to occur at higher rates, would only reduce the rate of increase in global primary energy requirements. This would nevertheless result in multiple benefits including lower resource requirements and lower environmental impacts.

Although the potential for energy efficiency improvements is high, the rates and time scale over which these improvements can be achieved are quite uncertain. The vintage structure of the energy system changes relatively slowly, especially for energy transport infrastructures and power plants. The typical duration of the replacement of old technologies by new ones is between 10 to 100 years. Fortunately, the diffusion is quicker for end-use devices, which are on average the least efficient components of the energy system, indicating that energy efficiency analysis and policy measures should increasingly focus on end use. At the same time, energy end use is one of the least documented and studied parts of the energy system. The analysis presented in this paper is based on estimates of global and regional energy end-use patterns, and as such can only be considered indicative. Further empirical research is required at both regional and national levels to create detailed balances from primary energy consumption to provision of energy services.

Although the potential for improvements in energy efficiency is far from being exhausted, it is quite clear that there must be, at least in principle, some upper bound limiting the minimum energy requirements for a given energy service task. The main deficiency of conventional analysis of energy efficiency improvements is that such an upper bound cannot be determined in a unique and methodologically sound way. The second law of thermodynamics specifies the maximum theoretical efficiency that can be achieved for any given task. The ratio of this minimum requirement to actual efficiencies then gives the actual efficiency improvement potential in much the same way as energy resource potentials are estimated. The efficiency improvement potential can also be considered a potential available to humanity much as other natural resources are.

Original points that the authors wish to stress:

a) Overall primary to useful energy efficiency of the world is less than 30%; exergy (second-law) efficiency is about 10%, and it is only a few percent for the primary to service efficiency.

b) Historical analysis of the energy system shows continuous efficiency improvements averaging about 1% per year.

c) Efficiency improvements of the energy supply are mostly technology-driven; energy end use depends more on lifestyles and may be susceptible to policy tools like demand-side management.

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