FUEL CONSUMPTION

FUELS AND ENERGY UTILISATION

Besides air, water, and food, humankind needs energy services: lighting, heating, cooling, pulling and pushing goods (actuators), transporting goods and people, and powering information devices (semaphores, radio and TV transponders, computing machines...).

We might question how much energy we need to satisfy our wanted services, but who knows the answer. If we look into the past, trying to extrapolate into the future, humankind energy expenditure has grown differently on different energy services:

- Energy used to procure food and water is now (say year 2000, per capita) five times larger than 10^6 years ago. This is the consequence of most people living in large service cities, and only few people devoted to provide food and water to all.
- Energy used for transportation is now sixty times larger than 500 years ago (the start of ocean travels). Is that surge in transportation-energy consumption really needed? Human mobility a basic human need, but to what extent? Is it not really a burden sometime, wasting nowadays several hours a day to go to work and back home?
- Telecommunication technology, on the other hand, seems no so energy-eager (compare a videoconference-meeting with a presence-meeting arranged via individual car transportation). However, every conceivable non-inert system (from biological organisms to just mechanical clockwork mechanisms) generates entropy, which must be evacuated as heat, and must be compensated by an exergy input to keep the process steady.

At present we only use two final-user commercial-energy carriers: fuels (piped or batch-delivered) and electricity (wired through the grid, or stored in batteries). Human metabolism needs some 100 W/cap (100 watts per capita), and humankind consumes some additional 1800 W/cap of final energy, coming from 2400 W/cap of primary energy: some 300 W of electricity (produced from some 900 W of primary energy, mostly from fossil fuels), plus some 1500 W of end fuels (refined from raw fossil fuels, and used for transportation, heating, and so on).

Most of the energy trade involves fuels, presently, in the past, and in the foreseeable future, as summarised in Table 1.

Table 1. Short summary of fuel share in world energy utilization.

Year 2000		Year 2020 prediction	
Primary energy[a]	Energy carriers (end use)	Primary energy[b]	Energy carriers (end use)
90% Fuels 7% Nuclear 3% Hydro	84% Fuels 16% Electricity Electricity production: • 66% Fuels • 17% Nuclear • 17% Hydro	90% Fuels 5% Nuclear 3% Hydro 2% Wind	82% Fuels 18% Electricity Electricity production: • 65% Fuels • 10% Nuclear • 15% Hydro • 10% Wind, solar...

[a]Gross values: 2400 W/cap (→$460\cdot10^{18}$ J/yr=10900 Mtoe/yr); population, $6.1\cdot10^9$ cap; GDP, 6700 €/cap.
[b]Gross values: 3200 W/cap (→$620\cdot10^{18}$ J/yr=14600 Mtoe/yr); population, $7.6\cdot10^9$ cap; GDP, 10000 €/cap.

When dealing with world-wide-average energy usage, we must recall how uneven (unfair) the distribution can be, with a third of mankind presently lacking electricity.

Fuel consumption

Fuel consumption, as fuel price and fuel availability, may be considered as market fuel-properties, and be jointly dealt with physico-chemical properties of fuels, treated aside, but we have preferred to deal with separately here.

The substances collectively known as fuels (basically coal, oil, gas, biofuels and synthetic fuels) are mainly used as convenient energy stores, because of their high specific energy-release when burnt with ambient air, a most fortunate situation, because a 15-fold (for hydrocarbons; a 34-fold for hydrogen) mass of air is required to burn a given mass of fuel, and air is freely available everywhere anytime (has not to be carried on). The burning process, however, is not essential for the release of fuel-and-oxidiser energy; the same global process takes place in fuel cells without combustion. Fuels, as energy source, are used for heat generation, for work generation, for cold generation, or for chemical transformations (see details in What fuels are used for). Fuels are also used for non-burning purposes, as for the chemical synthesis of materials, mainly polymers (fibres, plastics, cosmetics, pharmaceuticals, mineral oils, etc.), not considered here furthermore. In a summary, fuels may be used (chronological or difficulty ordering):

1. To produce heat in a burner (thermo-chemical converter). This heat may be used for direct heating, indirect heating (heat exchangers), for candescent lighting, for feeding a thermal machine (heat engine, refrigerator, or heat pump) to produce power, cold, or more heat, or for materials processing.
2. To produce work (and heat) in a heat engine (mechano-chemical converter). This work may be used to produce propulsion, or electricity, or cold, or more heat.
3. To produce electricity (and heat) in a fuel cell (electro-chemical converter). This electricity may be used to produce propulsion, cold, more heat, or for materials processing.

4. To produce materials (and heat) in a reactor (chemo-chemical converter); e.g. polymer synthesis, oils, perfumes...

Fuels may be considered as primary energy (i.e. directly extracted from natural sources and put on the market), as energy carriers or secondary-energy source (i.e. manufactured fuels such as crude-oil distillates and synthetic fuels), or as final energy (bought by the end-user for final consumption).

Fuel consumption, both as primary energy (i.e. as found in Nature) and final energy source (i.e. as input to the end user), is today the major contributor (near 90%) to energy use, both at source and at destination (up to the Middle Ages, animal power, water-mills and wind-mills were large contributors; in the far future, nuclear fusion might take over). The analyses of the utilization of: energy as a commodity (sources, transportation, storage and consumption) is sometimes called Energetics.

Fuels major share in world energy market (80% to 90%) means that the two terms, fuels and energy, can be used indistinctly both for primary and for final consumption. Beware, however, that some people used indistinctly 'electricity' and 'energy', without such a rational as above. On the other hand, it is worth considering that all terrestrial energy (except the minor contribution of gravitational tidal energy) is ultimately of nuclear origin: nuclear fission inside the Earth generates geothermal energy (also a minor share of the overall Earth energy budget), and nuclear fusion at the Sun providing the major energy input, that is partially converted in the short term (weeks) to hydraulic energy and wind energy, in the mid term (a year) to biomass energy, and in the very long term (million years) to fossil fuels, that is the dominant commercial source nowadays.

FUELS IN WORLD ENERGY PRODUCTION

Primary energy production (i.e. resource consumption) is computed from the budgets and estimates of industrial producers:

- Coal mines and coal importers
- Crude-oil extractors and importers
- Natural gas extractors and importers
- Nuclear energy generators
- Renewable energies: hydroelectric plants, wind-mill fields, solar energy fields, biomass industries, etc. Most of them are accounted basically by the subsidies they ask for.

The total primary energy consumption in the world (year 2000) was $460 \cdot 10^{18}$ J/yr (i.e. 11 000 Mtoe/yr, or an average of 15 TW in the world, or 2.4 kW average per person). Table 2 presents the distribution by type of energy source and its time evolution. Traditional energy balances are presented in toe-units (tonne-oil-equivalent) per year) or other odd units, but the average per unit time (e.g. in 10^{12} W=1 TW) seems a more rational rate measure and allows easier comparison with single power devices (e.g. with a typical nuclear power station of 1 GW). We agree that a year period is a more natural unit of time than a second, for human activities (who measures salaries in €/s?), but conversion errors and encumbrance are minimised if only SI-units are used, and one may use in most cases the simple approximation 1 yr=$30 \cdot 10^6$

s, which is less than 5% below the exact figure, since the data may have not higher accuracy (1 yr=$\pi\cdot10^7$ s gives less than 0.5% error). Besides, world averages have less dispersion than local ones (at a given instant, some places have daylight and others night, some have summertime and others winter). Some energy unit conversions are presented in Table 3 (e.g. $460\cdot10^{18}$ J/yr=$15\cdot10^{12}$ W=$130\cdot10^{12}$ kWh/yr=11 $000\cdot10^6$ toe/yr, that divided by $6.1\cdot10^9$ people corresponds to 2.4 kW/cap).

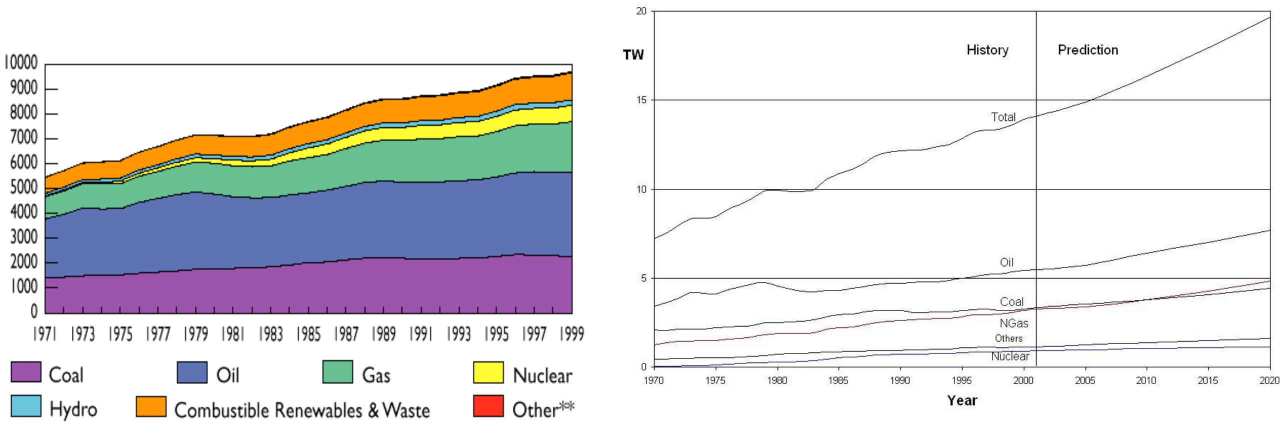

Fig. 1. Time evolution of world annual primary-energy consumption: a) in Mtoe, b) in TW. From IEA http://www.iea.org/.

Table 2. Primary energy consumption in % (year 2000).

	World ($460\cdot10^{18}$ J/yr)	First world ($250\cdot10^{18}$ J/yr)	Third world ($190\cdot10^{18}$ J/yr)	EU-15 ($65\cdot10^{18}$ J/yr)	Spain ($5.1\cdot10^{18}$ J/yr)
Fuels	90	86	95	81	85
coal	24	20	29	18	18
crude oil	36	41	26	43	53
natural gas	21	22	20	19	13
biomass (not traded)	9	3	20	1	<1
Nuclear	7	11	2	15	13
Hydroelectric	3	3	3	4	2

Table 3. Some energy unit conversions.

Unit	Equivalence		
Tonne oil equivalent (toe)	1 toe	=	$42\cdot10^9$ J
Tonne coal equivalent	1 tce	=	$30\cdot10^9$ J
Cubic metre of natural gas (STP)	1 m^3NG	=	$40\cdot10^6$ J
Kilowatthour	1 kWh	=	$3.6\cdot10^6$ J
Thermie (10^6 cal)	1 thermie	=	$4.2\cdot10^6$ J
Therm (10^5 BTU)	1 therm	=	$0.11\cdot10^9$ J
Barrel of crude (0.159 m^3)	1 barrel	=	$6.1\cdot10^9$ J
British Thermal Unit	1 BTU	=	$1.1\cdot10^3$ J
Kilocalorie (Calorie)	1 kcal	=	$4.2\cdot10^3$ J
Quad (10^{15} BTU)	1 Quad	=	$1.1\cdot10^{18}$ J
Exajoule	1 EJ	=	$1.0\cdot10^{18}$ J
Electronvolt	1 eV	=	$0.16\cdot10^{-18}$ J
Erg	1 erg	=	$0.10\cdot10^{-6}$ J

Notice that renewable energy sources (RES) in 2000, basically hydroelectric and biomass, only amount to a 10% of world energy coverage (6% in the UE) and all the rest come from exhaustible sources; there is a firm will however, to come back to a more sustainable exploitation of energy resources, and the objective is of covering by renewable sources up to 30% of the world energy production in 2020 and up to 60% in 2100 (UE target to 2010 is 12% of RES). Notice that 'resources' refers to the total amount in Nature, whereas “reserves” refers to that portion of resources that can be economically recovered at today's selling prices, using today's technologies and under today's legislation.

Per capita consumption of energy is oddly distributed (more than food, but less than water): the 2.2 kW/cap average comes from 4 kW/cap in EU, 8 kW/cap in USA, and less than 1 kW/cap in the Third World). It might be compared with the metabolic consumption of 0.1 kW/cap and the averaged Sun input on Earth of 30 000 kW/cap. Spain primary energy consumption is $5.1\cdot10^{18}$ J/yr=$120\cdot10^{6}$ toe/yr=4 kW/cap.

It may be interesting to compare fuel consumption (basically energy) to other basic human needs: world annual per-capita consumption is some 1000 kg of drinking water, 300 kg of oxygen from the air, 200 kg of solid food, and 600 kg of coal, 500 kg of crude-oil and 300 kg of natural gas (i.e. 1400 kg of traded energy-products; more if biomass from developing countries were added).

FUELS IN ELECTRICITY PRODUCTION

An intermediate step in energy utilisation (between primary consumption and final consumption) is energy transformation into a more useful form of energy, basically electricity production (but also town gas and coque production) from primary energy sources. In 2000, some 30% of all primary energy was used in the production of electricity, split by type of primary energy in Fig. 2 and Table 4. Notice that the major source for electricity is the combustion of fuels, in spite that many first-grade books say that electricity comes from water).

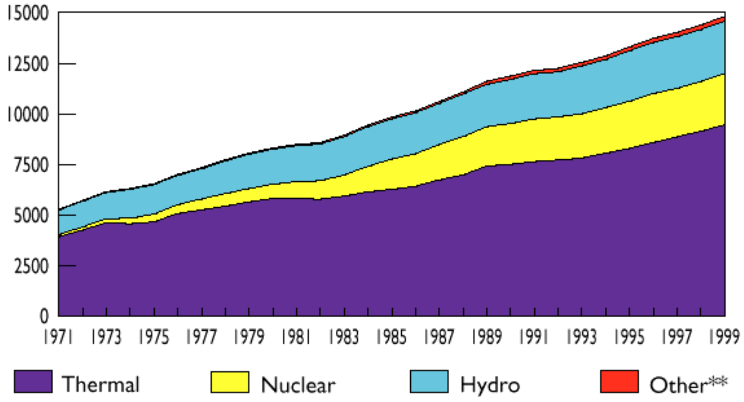

Fig. 2. Time evolution of world annual electricity production (in TWh. From IEA http://www.iea.org/.

Table 4. Electricity production: total and percentage by source type (year 2000).

	% in the world (1.7 TW= 15 000 TWh/yr= $54\cdot10^{18}$ J/yr)	% in USA (440 GW= 3900 TWh= $14\cdot10^{18}$ J/yr)	% in EU-15 (300 GW= 2500 TWh= $9\cdot10^{18}$ J/yr)	% in Spain (20 GW= 170 TWh= $0.5\cdot10^{18}$ J/yr)

Fuels	65		73		51		46	
coal		37		52		27		39
crude oil		9		3		6		3
natural gas		17		16		18		4
biomass (not traded)		2		2		-		<1
Nuclear	20		20		34		35	
Hydroelectric	15		7		15		19	

FUELS IN END-USE ENERGY CONSUMPTION

Final energy consumption is the energy finally consumed in the transport, industrial, commercial, agricultural, public and household sectors (it excludes deliveries to the energy transformation sector and to the energy industries themselves). It can be measured by type of final energy (Fig. 3 and Table 5) or by type of end use (Table 6).

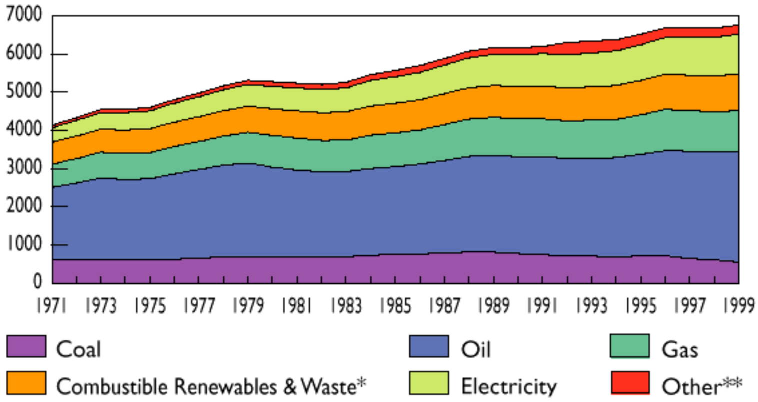

Fig. 3. Time evolution of world annual final-energy consumption (in Mtoe). From IEA http://www.iea.org/.

Table 5. Final energy use by energy type (year 2000).

	% in the world ($315\cdot10^{18}$ J/yr)		% in EU-15 ($44\cdot10^{18}$ J/yr)		% in Spain ($3.8\cdot10^{18}$ J/yr)	
Fuels	84		79		81	
coal		15		3		3
crude oil		41		56		64
natural gas		17		26		14
biomass (not traded)		13		4		-
Electricity	16		21		19	

The total final energy consumption in the world is $315\cdot10^{18}$ J/yr=$7000\cdot10^{6}$ toe/yr. The largest share in electricity generation is by coal (50% world-wide, 40% in EU). Final energy consumption in Spain is $3.8\cdot10^{18}$ J/yr=$86\cdot10^{6}$ toe/yr.

Table 6. Final energy use by sector (year 2000).

	% in the world ($315\cdot10^{18}$ J/yr)	% in EU-15 ($44\cdot10^{18}$ J/yr)	% in Spain ($3.8\cdot10^{18}$ J/yr)
Industry (construction, manufacturing, extractive)	30	32	35
Transportation	25	31	40
Commerce and services (offices, hospitals)	15	11	10

Residential (home)	20	23	15
Non-energy consumption	10	3	-

About 20% of world primary energy (30% of the final-energy consumption) is used to power transportation (1% coal, 90% oil-derivatives, 6% gas, plus 3% electricity). Some 17% of anthropogenic CO2 emissions also come from transport, being also responsible for some 20% of the projected increase in both global energy demand and greenhouse gas emissions until 2030. Fossil fuels will continue to provide the largest share in vehicle power consumption; EU forecast for year 2020 stills base >80% of that power from fossil fuels, with a rising on natural gas to 10%, supplemented by some 8% renewable biofuels and some 5% hydrogen (from fossil and renewable sources). Rough average energy consumption in transportation is:

- Per passenger: 3.0 MJ/km by plane, 1.8 MJ/km by car, and 0.9 MJ/km by bus or train. In equivalent fuel litres per 100 km, the figures are: 10 L by plane, 6 L by car, 3L by bus, and 2 L by train.
- Per tonne of freight: 3.0 MJ/km by truck, 0.7 MJ/km by ship and 0.5 MJ/km by train.

It is appropriate here to quote the CO2 emissions of different transportation means: some 250 g/(km·pax) for plains (down to 100 g/(km·pax) for the most efficient), some 200 g/km for cars (down to 130 g/km for new cars in EU from 2012), some 200 g/km for motorcycles, some 80 g/(km·pax) for buses, and some 60 g/(km·pax) for trains.

Nearly 40% of final-energy consumption in UE takes place inside buildings (heating, lighting, cooling and other appliances).

FUEL-TO-ENERGY CONVERSION FACTORS

Notice that the conversion from material budgets (coal, oil, gas, uranium) to energy budgets is an agreed standard and not the thermodynamic exergy (the difference is not very large however, except for nuclear fuels); the lower heating value is chosen for coal and oil, the higher heating valued for natural gas.

For nuclear power plants, a standard value of 33% in energy efficiency is assumed, taking no account of the amount of uranium used, i.e., for an amount E_e of electricity generated, a raw energy of $3E_e$ is accounted for (1 MWh→0.086/0.33=0.2606 toe). The actual amount of nuclear raw-material used depends a lot on the technology used; e.g. a given uranium-ore, would yield some 50 times more electricity if processed in a breeder reactor (where most of the fertile U-238 atoms transform in fissile Pu-239 atoms) than if processed in a normal reactor.

Similarly, a standard value of 10% in energy efficiency is assumed for geothermal plants.

Table 7. Recommended conversion factors.

Fuel	Ascribed energy
Coal bit.	0.58 toe/tonne
Coal black lignite	0.32 toe/tonne

Coal brown lignite	0.18 toe/tonne
Crude oil	1.02 toe/tonne
LPG	1.13 toe/tonne
Gasoline	1.07 toe/tonne
Kerosene	1.06 toe/tonne
Diesel	1.03 toe/tonne
Fuel-oil	0.96 toe/tonne
Natural gas	0.090 toe/thermie
Hydraulic energy	0.086 toe/MWh
Nuclear energy	0.2606 toe/MWh
Geothermal energy	0.86 toe/MWh

From IEA (International Energy Agency) data.

Talking about mass-to-energy conversion factors, it is worth mentioning that the main mass-percentage in fossil fuels is carbon, which burns with oxygen in the air to yield nearly four-times more mass of carbon dioxide (44 g every 12 g, from stoichiometry $C+O_2=CO_2$), so that in crude words, to release the average energy we trade in the world, per person and year, we are shovelling 1 tonne of carbon from below ground to the troposphere above us (and that tonne was bonded to some 0.2 tonnes of hydrogen, and is released bonded to 3.7 tonnes of oxygen); world CO_2 emissions in 2005 were $24\cdot10^{12}$ kg (6500 MtC/yr, from the 11 000 Mtoe/yr of primary energy).

Notice that final-energy consumption must be less than the primary-energy production, because of the 'unavoidable energy losses' in the production and transportation processes (e.g. world production 440 EJ/yr and world consumption 315 EJ/yr). Thermodynamics, however, just says that:

- Energy is conserved, in an isolated system, no matter the processes taking place.
- Exergy, i.e. energy available for work, in an otherwise isolated system in a given environment, can only decrease with time in every process.

From that, if the only energy need of humans were comfort heat, cooking power and even sanitary hot water, this final energy consumption could be met by extracting a much smaller primary energy from fossil fuels and forcing the rest of the energy to come from the ambient, like in a common heat pump, that produces three or four times the energy it consumes.

To measure energy-consumption efficiency, two ratios are used:

- Per capita energy consumption
- Per gross-national-internal-product energy consumption. Third-world countries consume three times more energy per GNP than developed countries.

Energy management

Energy is a first-need good, as food and water, and its supply has been traditionally managed by public administrations. The trend, however, is towards a free-market management with political restrictions (e.g. taxes on fossil energy) and incentives (e.g. subsidies on renewable energies) to procure the following social guaranties (safety, security, affordability and sustainability):

- Reasonable energy safety. Some risks always exist, and society and individuals must establish the level of acceptable risks (should you carry a gas-lighter in your pocket?, in an airplane?, should the domestic grid voltage be low or high?).
- Reliable energy supply. Some unreliability always exists, and society and individuals must establish appropriate levels of reliability, knowing that the costs grow exponentially (should a one-minute electricity-dropout in a commercial store be considered an admissible minor nuisance, or a great costly disturbance to be protected from?; how wide should the margin in supply voltage or frequency be acceptable?).
- Reasonable energy pricing. Should disperse occasional users (e.g. weekend second-residences) pay energy (and water, telephone, etc.) at the same price as central city dwellers? Should large energy consumers pay more or less per unit energy consumed?
- Reasonable energy impact on the environment. Some environment impact always exists, and society and individuals must establish the level of acceptable impact that energy utilisation (production, transportation and end use) may cause.

There are other aspects related to fuel consumption that have not been considered here: strategic reserves, strategy to fulfil demand variations, marketing policies, waste management, etc.

On the strategic dependence side, for instance, Europe imports more than 50% of the primary energy it consumes (in 2000, and it is increasing; in the case of Spain this external dependence is >70%).

On another side, to adapt electricity generation to demand, in view that electricity can hardly be accumulated, an order of power-plant activation priority is established, with non-storable hydroelectric, windmill and nuclear plants being always enabled, then cheap-coal and storable-hydroelectric power stations, and then combined-cycle natural-gas plants, that are more expensive to run. Besides, due to this changing-load effect, and particularly to the changing-input conditions (low hydraulic year, low winds, pre-programmed maintenance, unexpected shut-downs, and so on, the design capacity of available power plants must be larger than the expected average production.

ENERGY FUTURE

The future of energy (as a human commodity) looks dark nowadays, even darker than the future of clean water and food. The key problem is that energy consumption is growing not proportionally to population growth (as food may be), but at a much higher rate (because of the 'developed' way-of-life, and new energy demands from a crowed world, like massive water desalination), with two associated consequences:

- Environmental impact, because the largest share in energy production comes from fuel combustion, which generates global-warming gases and chemical pollution (global and local), and other energy sources do not show a clear alternative: nuclear fission has the unsolved problem of waste fuel and proliferation, and renewable energy sources are not so powerful neither free of environmental impact (e.g. effects of wind mills on fauna and landscape).

- Scarcity of cheap resources, because readily-available oil, gas, and coal deposits, are being exhausted at a quicker pace than new reserves are found.

As a clear solution to this energy problem is presently not at hand, the most rational approach might be to push along several fronts, looking forward to solving some of the inconveniences (being alert for new possibilities), and weighting more on those showing better promise at the time being. In particular:

- New fossil fuel plants seem to be unavoidable for decades to come, at least. Cleaner and more energy-efficient combustion processes must be develop for the traditional fuels, e.g. using natural-gas combined-cycle plants with a thermal efficiency nearly double than old coal-fired plants, capturing CO_2 emissions from traditional exhaust gases (e.g. using the carbonatation-calcination process), or helped by the oxy-combustion process, or directly from the fuel by reformation of the fossil fuel to less-contaminant fuels before combustion (what drives towards the hydrogen economy), etc.
- New nuclear fission plants can alleviate in the short term the energy problem, their problem with nuclear waste perhaps being solved in the future, but their remote risk of massive life destruction renders them too risky for wide-world proliferation (energy consumption in the future will increase the most amongst presently underdeveloped societies). Power plants intrinsically safe to runaway, intrinsically non-proliferating, and making best use of fissionable material, should be developed. Nuclear fusion research must be further encouraged, as being the only panacea in the horizon.
- New renewable plants must be promoted, even subsidized if one takes account of the social costs implied in traditional power plants (from human health to world politics), but not as a present panacea: nowadays, they cannot provide a complete substitute to fossil-fuel plants, nor in decades to come. Among renewables, the two approaches with wider future are, first, biomass cultures for biofuels (from non-alimentary plants), and second, thermal solar energy plants, although wind energy is developing faster, at present.

Perhaps the best summing up is:

- Make people aware of this gigantic energy-problem by fostering scientific and social education. Public acceptance is a pre-requisite in developed societies, without which, economic criteria and technology availability are powerless.
- Make energy economy more explicit (including waste management and health-care costs), for consumers to minimize the real cost/benefit ratio. Energy seems to be presently too cheap for people to care about (e.g. when buying powered appliances, or when using vehicles), or too rigid to allow for sensible choices (e.g. biofuels are not yet alternatives vehicle fossil-fuels).
- Invest in basic and applied research on energy management and related environmental impact. There is no proportion between the ratio of R&D expenses and consumption expenses, between energy technologies and other technologies.
- Meanwhile, diversify the effort according to actual achievements (facts) and reasonable expectations (expert prospective; without preconceptions, fears and utopias). Avoid being too enthusiast on a single goal; the best energy diet may be, as for a food diet, variety and

temperance (with green matter being preferable to meat, and paying attention to 'oysters and lobsters').

References

- www.worldenergy.org. World Energy Council (WEC); a UN-accredited non-government, non-profit organisation.
- www.iea.org. International Energy Agency (IEA); a 26-member-states policy-advice cooperative agency.
- http://europa.eu.int/comm/energy/index_en.html. European Union's Directorate-General for Energy and Transport.
- http://www.bp.com/statisticalreview. BP is a global energy company.

Back