THE FUTURE OF ENERGY

Carlo Rubbia
ENEA

Opening remarks at the 18th IAEA Fusion Energy Conference
Sorrento, Italy, 4th October 2000

TABLE OF CONTENT

1.— Energy is necessary.

The interest of politicians, businessmen, technologists, scientists and the people at large is focused today on the problem of energy. Everybody will agree on the fact that "Energy is necessary" for the future of mankind. But many tend to paraphrase this by saying that "Energy is a necessary evil". No objection to the necessity: but an analysis of the motivations for regarding energy as "evil" reveals some Freudian undertones. This scepticism towards technology, as a solution to the rising environmental concerns, perceived as a Faustian deal, after centuries of a passionate technical endeavour deeply engraved in our conception of the world, is a curious phenomenon to say the least. All these problems and the associated concerns are serious: the inevitable growth of energy consumption under the sheer momentum of society and the very human expectations of the poor, may indeed add enough yeast to make them leaven beyond control. However, like in the case of famine, illness etc., also here Science and Technology should be trusted; indeed there are reasonable expectations that, combined, they will have the possibility of solving also this problem, in full accord with the economic, dynamic and technical constraints that a working system has to comply with.

That energy supply has been a major element of our civilisation may be evidenced in Figure 1 (R.A. Knief, 1992) where the approximate energy pro capita from the beginning of mankind (planetary average) as a function of time is shown. Energy for food gathering has been supplemented by the one for household use (initially heating), organised agriculture, industry and transportation. Hay for working horses[1] is included, the equivalent of diesel for trucks and tractors today.

The total energy consumption of the most advanced part of mankind has grown about 100 fold from the beginning of history, reaching today the level of about 0.9 GJ/day/person (the value of Figure 1 relative to the planet as a whole is 0.2 GJ/day/person). This corresponds to the equivalent of burning 32 kg of Coal/day/person, or a continuous, averaged supply of 10.4 kWatt/person. As a

[1] Still in 1899, in the USA about two thirds of the mechanical energy actually came from horses.

reference the food energy supply of 3000 kcal/day corresponds to a thermal, continuous power supply of 0.14 kWatt/person. Hence the energetic food supply represents a mere 1% of the total energy need of each of us.

The total energy production integrated over the planet, mostly coming from fossil fuels, corresponds to a continuous power production in excess of 10 TWatt. As a comparison, the geological heat from the earth's crust due to natural Uranium and Thorium decays is about 16 TWatt. Incidentally, this represents the totality of geothermal stationary energy. Hence mankind has roughly doubled the internal energy generation of the planet. The portion of the earth's kinetic energy transformed into lunar and solar tides in the hydrosphere is an averaged power of 3.49 TWatt. There is not much power to harness out of the tides of the sea !

Over the last 150 years, the energy consumption of the planet has steadily increased at the rate of 2.3 %/year (Figure 2a). Note the mysterious oscillatory behaviour due to the so called Kondratiev cycles of about 54 years (Figure 2b) There is no doubt that the world's consumption will continue to grow in the future, since the world's population is steadily growing and billions of people in the Developing Countries strive for a better life. The present, enormous disparity in energy consumption (Sweden's 15'000 kWatth of electricity/person/year, Tanzania's 100 kWatt h/p/y) will tend to converge.

There is also no doubt that energy will have to be produced and used in a more efficient way: but this is a necessary but not sufficient condition for a stabilisation of the energy consumption. We will undoubtedly get more mileage out of a litre of petrol, but there will be more cars, light bulbs will have a better efficiency but there will be more light bulbs, etc. We shall witness a better efficiency, but also a strong increase of energy consumption. We know that the so-called energy intensity, i.e. kWatt h for dollar earned is roughly a constant, slowly varying with social conditions and time. The world's economic forecast is of a GNP growth of about 2%/year. It is not an accident that this is roughly also the expected energy growth planet-wide.

Such a large consumption raises obvious questions on the longevity of (fossil) resources. There is also no doubt that in order to sustain the pace of growth of our civilisation, some new massive energy sources will be needed in the long run (Figure 3).

The longevity of the survival of the necessarily limited fossil's era will be affected on the one hand by the discovery of new, exploitable resources, strongly dependent on the price and on the other by the growth of the world's population and their standard of living.

It is generally expected that the world's population will grow to a level of the order of 10^{10} people by about the end of the century and remain stable after that. Assuming then an average energy consumption equal to the average European value pro capite of 3 TEP/y (TEP ≡ ton equivalent of Oil), we find that asymptotically — I would add roughly by the time fusion will be deployed — the (uncurbed) need for an averaged, total world's power production of the order of 39 TWatt, or about three times the present level. (Incidentally an exponential growth at +2.3 %/y as evidenced in Figure 2 would lead to this value in 55 years).

At the present consumption level, known reserves for coal, oil and gas correspond to a duration of the order of 230, 45 and 63 years (Figure 3). Natural uranium, used as at present (^{235}U, MOX will not help much) has known reserves for 54 years. These numbers will be affected positively on the one hand by the discovery of new reserves, and negatively on the other by the increased consumption. Even if these factors are hard to assess, taking into account the long lead time for the development of new energy sources, the end of the fossil era is at sight. And what after that ? (Figure 4).

2.— The Greenhouse Issue.

The utilisation of fossils may have to be curbed prematurely by environmental considerations i.e. the greenhouse effect, for which mankind's main alternative is whether to fight it or to accept it. It should be said that with a massive greenhouse effect, tomorrow's world will not be necessarily worse for everybody (Siberia and North of Canada stand to gain, others like Mediterranean countries stand to lose, because of growing tropical illnesses, desertification, drought, deforestation etc.) : it is clear that tomorrow's world will be very different and, what is more worrisome, substantially unpredictable.

It is evident, that for the first time in history, human activities begin to modify the global conditions of the planet. We begin to realise that the *price* which the community has at the end to pay for a Barrel of Oil — in view of the environmental effects — is significantly higher than the *cost* charged by the producers. These recent, widespread preoccupations are now politically formally recognised (I could say rubber-stamped) by the Protocol of the Kyoto Conference, which has introduced a new dimension to the problem. This in turn has indicated the existence of a potentially much closer limit to fossil utilisation than the sheer natural supply.

It must be said that, though global warming of the planet and the CO_2 rising content in the atmosphere are not controversial, the phenomenology is very complex and the relationship of cause to effect is still somewhat controversial because (1) of the very large amount of CO_2 for instance exchanged between the sea and the atmosphere, some 30 times larger than man's emissions; (2) of the presence and the role of other greenhouse gases like for instance methane and chloro- fluoro- compounds and (3) the intrinsic instability of the climate of the planet, subject to large variations even prior to the advent of our technological era.

Anyway, the most elementary prudence suggests that CO_2 emissions due to man's activities, today (1990) amounting to some 15 Gtons/year, should be progressively and significantly curbed. It must be stressed however that curbing the CO_2 emissions does not necessarily mean a total ban of fossil fuels. Indeed new methods are emerging, in which the CO_2 produced can be disposed safely. CO_2 is liquid at about 73 atmospheres (30 °C), i.e. at about 700 meters ocean depth. Depleted oil and natural gas fields for instance can absorb CO_2, if it can be pumped back underground.

There is no doubt that the — now deemed necessary — curbing the CO_2 emissions will cause a substantial increase in the cost of energy. These methods in turn will enhance the development of alternative energy sources and spur the development of systems combined with CO_2 separation and disposal with the use of Hydrogen as a clean energy carrier as substitute for natural gas and as well as for the supply of high efficiency fuel cells. An important asset of this substitution is the basic interchangeability between natural gas and Hydrogen, in the sense that a large majority of the existing installations may be retro-fitted from one to the other.

3.— Energies for the Future.

Very many individuals, committees, working groups etc. have exercised their forecasting capability, predicting the energy mix for the future with a variety of scenarios. A common element to all these predictions is however the rise of the demand, roughly at the level of about 2 %/year. There are two main approaches to the question:

1) the "continuity" approach of Marchetti, (Figure 5) who makes use of the epidemic equations to fit the past energy pattern in order to extrapolate for the future. In this scheme there is in the future, as it has been in the past, a dominant energy source. Transitions occur at the Kondriatiev's maxima of energy consumption, in correspondence of a surge in the energy prices. These transitions are technology and economically driven, rather than caused by availability of resources. In his prediction, the next dominant phases are (i) natural gas with a maximum in 2030, followed by (ii) fission driven "new nuclear", with a maximum in 2090, (iii) eventually followed by a choice between solar and/or fusion during the next century. The duration of all cycles are the same and they are symmetric around the maximum.

2) The "energy mix" approach for instance by the World Energy Council (Figure 6, Shell Planning Group), in which a number of different, novel technologies, still to be developed, take progressively the place of fossils, which already by 2050 represent no more than 1/3 of the total primary energy supply. These new technologies are Wind, new Bio-mass, Solar, Geothermal and a "Surprise" to be defined, which develop quickly after circa 2020, in an explosive manner. Classic, fission driven nuclear energy survives, but at a modest level. There is no contribution of Fusion, at least until 2100. Their assumption on Geo-Thermal must be discarded, since it has been unrealistically assumed an averaged power of about 3 TWatt, while, as already pointed out, the geological heat from the full earth's crust is a mere 16 TWatt.

Contrary to the Marchetti approach, in which a continuity with the past and purely economic considerations are dominant, the "energy mix" approach puts an extraordinary faith in the capability of technology of introducing new, ecologically driven methods for energy generation. These methods imply also a spatially distributed network of relatively small scale devices rather than centralized sources, as it is the case for instance today for electricity production. The main concern about this second approach is that the new renewables (solar, wind, etc.) though they may acquire a very important role in the medium and long range, may not be enough to sustain the future expectations on their own, which, for instance for 2060, assume an averaged total power production in excess of 30 TWatt, mostly coming directly or indirectly from the Sun.

4.— How much Energy from the Sun ?

The total annual, primary solar direct radiation energy, collected in the most favourable locations of the Sun belt is of the order of 2500 kWh/m^2, corresponding to a time averaged power of the order of 280 Watt/m^2. (Here in Sorrento we have about 2/3 of such a value). Including diffused light, the energy density is about 30% higher.

The total active surface to collect the indicated power of 30 TWatt is about $S_{coll} = 1.07 \times 10^5/\eta \ km^2$,where η is the conversion efficiency of the primary solar energy into useful energy. Note that the total, cultivated area of the planet is about 10^7 km^2. The efficiency is about $\eta \approx 0.1$ for photo-voltaic (the occupational area must be scaled by a factor taking into account the space between captors) and that and $\eta \approx 0.005$ for new bio-mass (fast growing trees, for which incidentally also abundant water is required)[2].

In order to compare directly solar to nuclear (either fission or fusion), we consider the thermal solar option, in which the sunlight is concentrated by mirrors in order to produce high quality heat, typically of order 500 ÷ 800 °C or even higher. The peak power density of solar light is about 0.1 W/cm^2. If concentrated by a factor 2000, it gives a power density of about 200 W/cm^2, the same as the one from rods of a fission reactor, and in principle exploitable in a similar way. Concentration factors up to 10^4 have been obtained with solar towers (Figure 7).

[2] In the case of wind energy (50 m tall towers, 33 m diameter helices separated by 1.25 diameters on average, class 4 wind) the required area for a given average power is about ten times the one of photo-voltaic.

A typical LWR produces a fission driven thermal power of ≈ 3.0 GWatt$_{(t)}$. In order to harness this amount of solar thermal power, the effective collector's surface must be of the order of 10 km^2. In practice, taking into account the inevitable light losses of the optics (about 50%), the actual collector area should be about twice as large, i.e. ≈ 20 km^2.

The solar plant is essentially a heat generator. High temperature heat is the standard entry point for electricity production. With the development of a hydrogen market, it could become also a source of hydrogen from water dissociation. Let us compare the costs of the nuclear and the solar options, the cost of the subsequent heat utilisation being the same for both. The cost of the heat generating part of a standard 3.0 GWatt$_{(t)}$ LWR is nowadays of the order of $1.5 \div 2$ \$US Billion. For a competitive investment cost, the 2×10^7 m^2 system of solar collecting mirrors should then cost no more than about $75 \div 100$ \$/m^2. At present, its cost is about 200 \$/m^2, but based on a world-wide installed solar thermal power of 350 MWatt (peak). In view of the huge scale factor (10^5 and up), a factor $2 \div 3$ reduction in cost is not too extravagant.

If properly constructed, the duration of operation of a solar plant should be comparable to the one of a LWR, namely 40 years or more. Its maintenance costs are definitely smaller and fuel cost is strictly zero. There is no fuel to produce, to handle or to dispose.

Solar power utilisation generally requires an effective energy storage, in order to smooth out daily variations. This is currently performed heating a molten nitrite salt (melting point 220 °C, stable to about 600 °C) which is kept in a low thermal leak storage tank. This technology is very mature and there are many substances at low cost which can be heated to the required temperature, acting as thermal storage. In the case of a exceptionally extended low solar yield, an additional heater operated with fossil fuel can be operated as a backup.

Clearly the solar thermal option could be made cost competitive with other present forms of energy, provided they are deployed on a sufficiently large scale. If η, the conversion efficiency of the primary solar energy into useful energy is made sufficiently large, (for instance in the case of solar thermal the heat collection is probably 0.50, which combined with a thermo-dynamical efficiency of 1/2 could give $\eta \approx 0.25$) the amount of land required becomes quite reasonable.

For instance, Italy's electricity yearly consumption is about 300 TWatt h. If we were to produce 90% of them with solar thermal stations and $\eta \approx 0.25$, the area covered by captors would be about 400 km^2 and the occupied, uncultivated land about 1000 km^2, i.e. about 1/300 of the total country's surface, which is not exorbitant.

5.— Conventional Nuclear Power.

When nuclear energy was first developed in the sixties, it was greeted with the greatest enthusiasm. (We recall for instance the international, UN sponsored "Atoms for Peace" programme in Geneva in 1959). It promised an unlimited, cheap and abundant source of energy for the future of mankind. In the course of the years this enthusiasm has gradually disappeared and today nuclear power is perceived by many as "evil". Under the pressure of popular concern, a huge number of regulatory constraints have eroded the price margin of nuclear energy, which today does not seem to be any longer "the cheapest energy", especially when compared to fossils and in particular Natural Gas and Coal.

The apriori predicted features of nuclear energy, when compared to fossil fuels, are (1) potentially zero emissions and (2) an extremely parsimonious use of the fuel. For instance 1 ton of Uranium — provided is completely fissioned ($\eta = 1$) — could produce the equivalent energy of 14 Million barrels of Oil (BOL) or 3 Million ton of Coal (TEC). There is therefore a potential gain in the power yield of about 3×10^6 with respect to chemical energy. The present, planetary demand of energy (10 TWatt) could be ideally exhausted with about 3900 ton/year of fully fissile material. If fission is replaced with fusion (D+T), the primary, natural Lithium consumption in the same conditions will be a mere 16'000 ton/year, from which 6'800 ton/year of T is bred, however unstable with 6.6×10^{13} Cie/year.

Unfortunately the present nuclear power technology, essentially based on Light Water Reactors (LWR) operated mostly on enriched Uranium and thermal neutrons, is far from such an idealised expectation. Only the ^{235}U (0.71%) of natural Uranium is directly fissile, of which about 60% is extracted by enrichment. Therefore only about $\eta = 0.4\%$ of the potential energy contained in the natural Uranium is energetically used.

For instance in order to produce 1 GW_e x 30 years ≈ 6.1 TWh one has to handle 4.50×10^7 ton of high content (2000 ppm) Uranium ores, to be compared with 3.21×10^8 ton of coal mining for a Coal fired plant, a factor 7 in mass but with a much easier handling. The conclusion is that most of the "magic" nuclear factor of 3×10^6 of nuclear energy is, as of today, almost wiped out.

This is why, in spite of the tremendous potentials of nuclear energy, if used in this way, there will be no more energy for future use from Uranium than from Oil.

There are additional important arguments which play in disfavour of a purely LWR based nuclear energy option —if it has to be generalised:

(1) The problem of the long lived radioactive waste. Existing nuclear power plants produce annually about 12'000 tons of highly radioactive spent fuel, of which about 1% (120 tons) are Plutonium. The radio-toxicity of this mass of material reaches the level of the initial Uranium ores only after about 1 million years

(2) Emission of long lived radioactive isotopes (gases, etc.).

(3) Criticality accidents, which have almost doubled the dose to population.

(4) Links to military applications. The critical mass of the Plutonium from a LWR is only some 30% larger than the one of bomb-grade ^{239}Pu. An ill-minded group of individuals may realise quite terrifying devices — especially in Developing Countries, intrinsically more unstable because in a rapid evolution.

(5) The thermo-dynamical efficiency, which is about 33% for LWR's, related to the actual level of technological development in the late sixties. In order to keep its competitive edge, nuclear energy has to abandon the saturated steam option, for instance for gas cooling.

To conclude, and in order to harness realistically the immense potential energy inside nuclei as a major energy source for the next century, according for instance to the "continuity scenario", very tough, revival conditions must be satisfied, which, in turn, will inevitably demand new methods and new ideas. In addition, we must use, far more efficiently, a naturally abundant fuel in order to secure its wiser use and practically unlimited resources. Both Fusion and Accelerator driven Fission have a chance of achieving such a goal.

6.— A Renovated Nuclear Scenario.

Energy is released whenever low Z nuclei fuse or high Z nuclei fragment (packing fraction). This leads to two substantially different breeds of devices: Fusion and the Accelerator driven Energy Amplifier (fission). Both methods hold the remarkable promise of $\eta = 1$, namely full combustion of an initial, natural fuel and of virtually unlimited natural resources:

(1) Fusion, in its simplest form, consists of the magnetically confined burning of Tritium (^{3}H) through the reaction:

$$ {}^3_1H + {}^2_1H \rightarrow {}^1_0n + {}^4_2He + 17.6 \ MeV $$

The unstable Tritium($t_{1/2}$ = 12.33 y) is produced by "breeding" from Lithium, using the produced neutron:

$$ {}^6_3Li + {}^1_0n \rightarrow {}^4_2He + {}^3_1H + 4.8 \ MeV $$

Additional ${}^3_1H$,which is needed to compensate inevitable losses, comes from the (fast) reaction ${}^7_3Li + {}^1_0n \rightarrow {}^4_2He + {}^3_1H + {}^1_0n$, in which the neutron is not destroyed. In this way we can achieve a breeding equilibrium, namely a situation in which the amount of ${}^3_1H$ produced and burnt are the same. The main shortcoming of this reaction, the easiest to achieve, is that the bulk of the produced energy is carried by the fast (14 MeV) neutron, which, through secondary interactions, produces a considerable amount of activation in the reactor's structure.

(2)More advanced Fusion reactions promise less radioactive activation. Another reaction would be possible with an initial deuterium-helium 3 mixture

$$ {}^3_2He + {}^2_1H \rightarrow {}^4_2He + {}^1_1p + 18 \ MeV $$

in which, however, some neutrons (6%) are produced in deuterium-deuterium collisions ${}^2_1H + {}^2_1H \rightarrow {}^3_2He + {}^1_0n + 3.27 \ MeV$. The main shortcoming of this reaction is the lack of availability of ${}^3_2He$. The best one has been able to offer so far is to gather this fuel on the Moon, where it is accumulated as the result of the Solar Wind. It is hard to believe that thousand of tons of fuel could be brought back to Earth in an economically convincing fashion.

(3) One of the ultimate advantages of Fusion with respect to Fission, is that there are several exothermic reactions which produce no neutrons, neither directly, nor indirectly through secondary reactions. Since neutrons are the primary sources of

activation, this will be a tremendous asset, making the reaction inherently "clean". It is probably in this way that an ultimate nuclear energy will be eventually exploited in a very far fetched future, excluding the possibility of a "Cold Fusion". The simplest reaction of this kind is

$$ {}^{1}_{1}p + {}^{11}_{5}B \rightarrow 3\left[{}^{4}_{2}He\right] + 8.78\ MeV $$

which unfortunately is known not to "ignite" in a magnetically confined device (Tokamak) and most likely also with inertially confined Fusion. Note that this reaction does not produce any γ's or neutrons. Both Hydrogen and ${}^{11}_{5}B$ (81 % of natural Boron) are extremely abundant and easily obtained. So far unknown methods are needed in order to exploit such a formidable asset.

(4) Coming to Fission, the Accelerator driven Energy Amplifier (EA) is based on the fission reaction (FF: Fission Fragments)

$$ {}^{233}_{92}U + {}^{1}_{o}n \rightarrow 2.33\left[{}^{1}_{o}n\right] + 2FF + \ 200\ MeV $$

driven by neutrons from a high energy Accelerator. Just like in the case (1) of Fusion, ${}^{233}_{92}U$, which does not exists in nature, is bred from natural Thorium by the reaction induced by secondary neutrons

$$ {}^{232}_{90}Th + {}^{1}_{o}n \rightarrow {}^{233}_{91}Pa + \gamma \xrightarrow{\beta-decay\ (27\ days)} {}^{233}_{92}U + {}^{o}_{-1}e $$

An external supply of neutrons, provided by an accelerator is necessary, since the neutron producing reaction gives 2.33 neutrons, while 2 neutrons are needed to close the breeding cycle. The difference being 2.33 – 2.00 = 0.33, because of the inevitable neutron losses, it is hard to sustain criticality.

Like in the case (1), a breeding equilibrium is reached, in which the amounts of ${}^{233}_{92}U$ produced and burnt are equal. The EA can burn completely also the additional elements which are produced by ${}^{233}_{92}U$ capturing neutrons (5%) and the subsequent reactions, in secular equilibrium with the main ones. Therefore, in contrast with the LWR's, the EA achieves complete burn-up by fission of the initial ${}^{233}_{92}Th$ in a closed actinide cycle and therefore $\eta \approx 1$. The only "waste" left are Fission Fragments, which have a strong but less lasting activity.

Both Fusion and Fission devices listed above are non-critical devices, in which, in addition, melt down has been rendered impossible. In both devices a fraction f of the produced (electric) energy is re-circulated, either to heat-up the plasma or to run the accelerator. This fraction $f = 25 \div 30$ % for devices of type (1) i.e. D-T magnetically confined Fusion and $f = 5 \div 10\%$ for the EA, type (4).

The main motivations for the Research and Development of new sources of energy from nuclei is that of *reconciling the inherent advantages of such powerful and virtually unlimited energy sources with an environmentally acceptable and safe new technology*. This has been the main thrust behind Fusion and it explains why so many people have been working so hard for such a long time in order to achieve it. The by far less ambitious development of the Accelerator Driven Energy Amplifier stems from the same objectives. It is therefore reasonable that the potentialities of both methods (1) and (4) are compared and critically assessed (Figure 8).

7.— The Energy Carriers.

So far we have considered the possible alternatives for the primary energy sources. However of fundamental importance is also the choice of the "energy carrier" from generation to use, especially taking into account that both in the case of solar and nuclear (see for instance the concept of the Canton Island of Marchetti) the distance between the points of production and of use will necessarily stretch over much longer distances.

We are witnessing a progressive increment of fractional use of electricity, with an increase pro capite in the developed countries from 1100 kWatt h/person to 25'000 kWatt h/person in less than 100 years. One can visualise three main steps of the electricity penetration into the market (Figure 9).

Evidently electricity alone cannot be the only future carrier. Many applications now based on fossil fuels (oil and gas) cannot be immediately converted to the use of electricity. For these applications, the use of hydrogen is emerging. It should be stressed that hydrogen and electricity are the only two energy carriers which produce no harmful emission at the point of use and, by themselves, also at the point of production.

Hydrogen (H_2) promises future uses which are unique and make it much more valuable than just another ignitable material. The introduction of H_2 as an energy carrier requires no major technological breakthroughs. It is technically feasible to replace oil and natural gas with H_2 in virtually all present uses.

H_2 can be stored, transported and delivered using technologies which are similar to the ones widely used for natural gas. H_2 has a smaller density than methane (0.0899 vs. 0.714 gr/litre ntp) and a combustion energy per unit volume which is only 1/3 (12.76 vs. 39.7 kJ/litre ntp). Diffusion is larger by a factor almost three, which implies tighter seals. But it will flow more easily through a pipe, about a factor 2.8 faster. A pipeline designed for natural gas will transport H_2 at the same pressure, but with only 80% of the energy flow. One can expect that the cost of transmission for unit energy of H_2 will be about 50% higher than for natural gas.

When H_2 is burnt in air the only pollutants are nitrogen oxides (NO_x), which is however strongly reduced, because of the presence of H (H_2O). Catalytic heaters, suitable for small scale applications, operate at lower temperatures than ordinary combustion, reducing NO_x emission to a negligible level.

Fuel cells permit the direct transformation of H_2 into electricity at a theoretical efficiency of 0.83 (enthalpy limit), though practical performance is lower (0.5 ÷ 0.7). This is about two times higher than ordinary turbo-generators or vehicle engines, produce no NO_x and a much smaller waste heat. This waste heat, if at sufficient temperature , f.i. 800 °C) can be recovered with conventional methods (turbine) further increasing the efficiency.

Studies on relative safety of H_2 methane and gasoline have concluded that no one fuel is inherently safer than the others in every respect, but that all three fuels can be and have been used safely. Hydrogen-rich gases have been used for home heating and cooking for more than a century. "Town-Gas" is a mixture of approximately half H_2 and half CO and it has been generally used in most developed countries before natural gas became widely available.

Producing H_2 from fossils allows CO_2 sequestration, thus reducing emissions to zero. It can be efficiently produced by water dissociation with high temperature nuclear heat (800 °C). Finally H_2 is the most obvious "storage" for solar energy.

8.— Conclusions.

To conclude, in the medium and long run, fossils most likely will not be capable to produce substantially more primary power than what is available today. The factor about three in power demand forecasted for the middle of this century (according to ≈ 2% yearly increase of demand) must be met with different and innovative technologies, of which two seem to be most promising, namely (i) solar and (ii) new nuclear.

Solar energy is abundant and if used efficiently could produce the energy needed for a long time to come. In particular the solar thermal approach seems rather promising, in the sense that it can be made rather efficient ($\eta \approx 0.25$), it uses standard technologies for heat conversion and utilisation and it has potentialities for a price competitive to other sources. An advanced photo-voltaic (at present $\eta \approx 0.1$ and with higher unit area cost) may take over at a later date. However meaningful utilisation of this form of energy is limited to the "sun belt" of relatively desert and sunny lands, fortunately of large proportions, but often very far of the main centres of human activities. It requires the development of a renovated system of energy carriers in which (i) electricity and (ii) hydrogen are the main contendants.

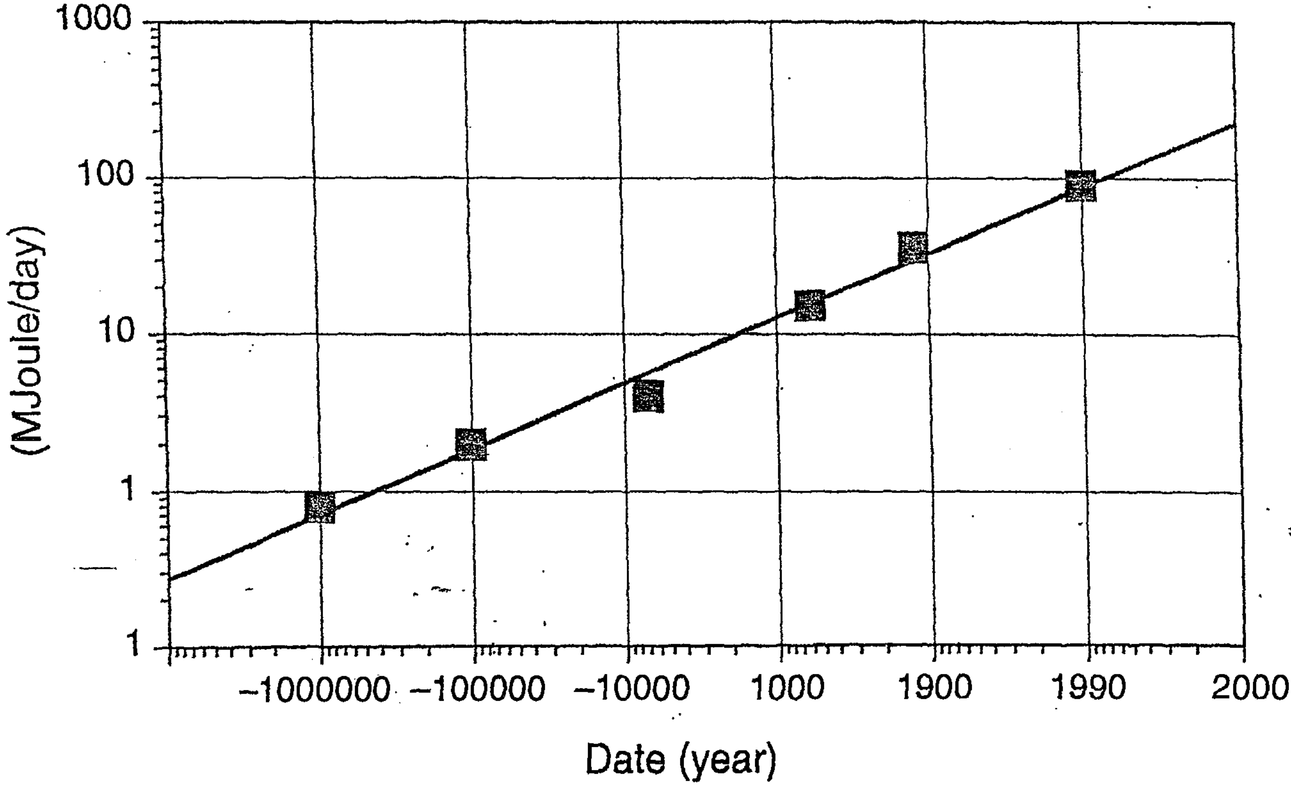
There is no such a theorem which says that all forms of nuclear energy should be necessarily bad. But, in order to be applicable on a vast scale, energy from nuclei must undergo a deep transformation and very tough, revival conditions must be satisfied, which, in turn, will inevitably demand new methods and new ideas. There is no doubt that the environmental and safety features will govern any new development in the field of energy from nuclei. In addition, we must use, far more efficiently, a naturally abundant fuel, in order to secure its wiser use and practically unlimited resources. A renewed nuclear approach must be based on full breeding of a natural element, either through Fusion or through Fission. In both options the potentially available energy, though not strictly renewable, can realistically last for many tens of centuries at a few times the present consumption.

But even if its wide and economically competitive use may be questioned, Fusion should be pursued as such, since it is exploring a fundamental domain of basic science. There are two main forms of high temperature matter in Galaxies: (1) the low density high temperature gases, mostly hydrogen, gravitationally confined in space (2) and the high temperature and very high density compressed matter in the interior of stars. These domains correspond roughly and respectively to magnetically confined and inertially confined Fusion. They must be both thoroughly studied in order to better understand the Universe. For me, Fusion is and remains an essential field of Fundamental Science, worthwhile pursuing vigorously.

Let me conclude with an anecdote related to Benjamin Franklin. His minister for finance asked him what was really the interest of studying electricity with flying kites. His answer was: "I do not really know, but I am sure that one of yours successors will put a tax on it !"

9.— Figures

Average Energy Consumption per person



Approximate per capita consumption of energy as a function of time [R. A. Knief, 1992]. Energy for food gathering has been supplemented sequentially by that for household use (initially heating), organised agriculture, industry and transportation.

Figure 1

Figure 1.

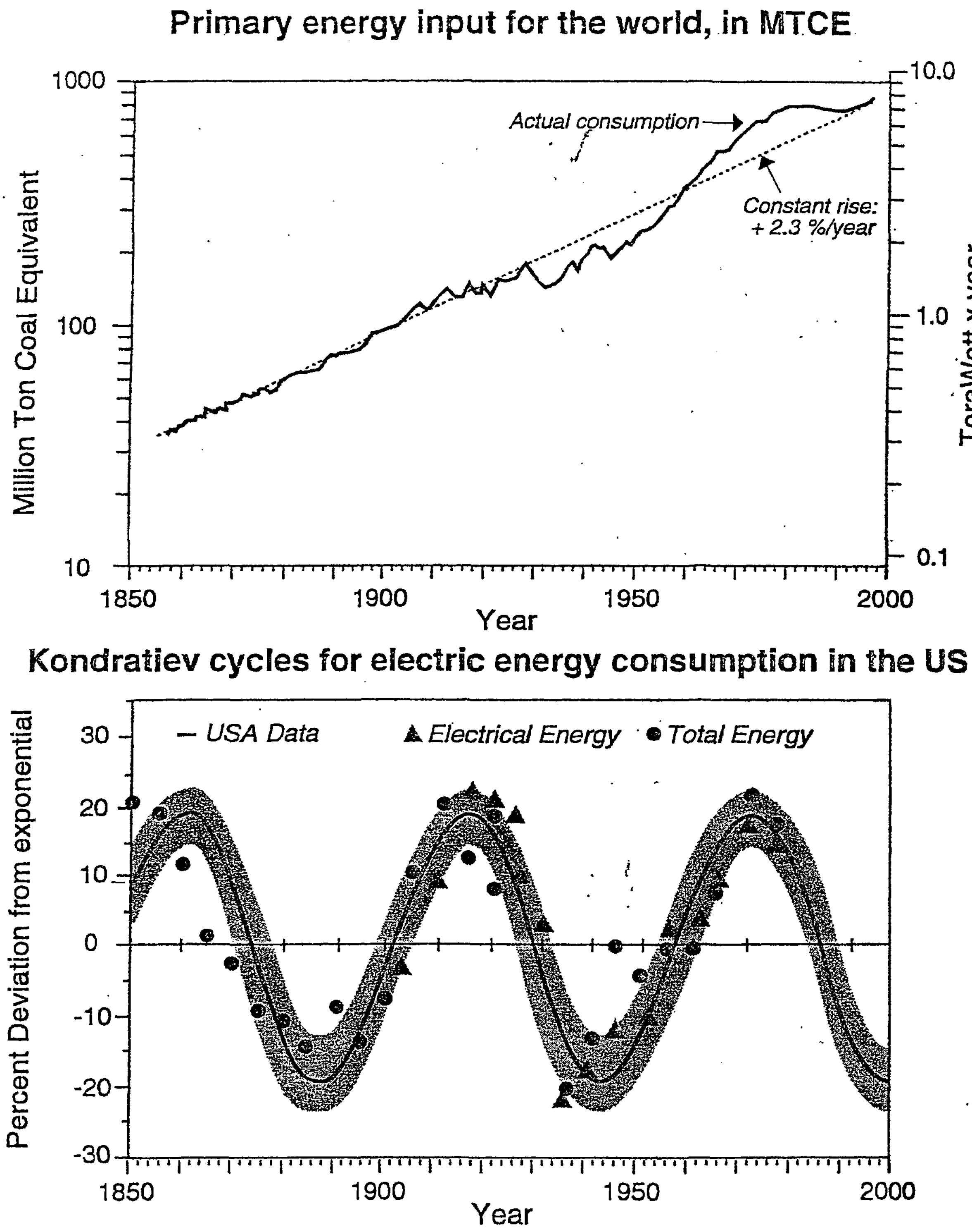
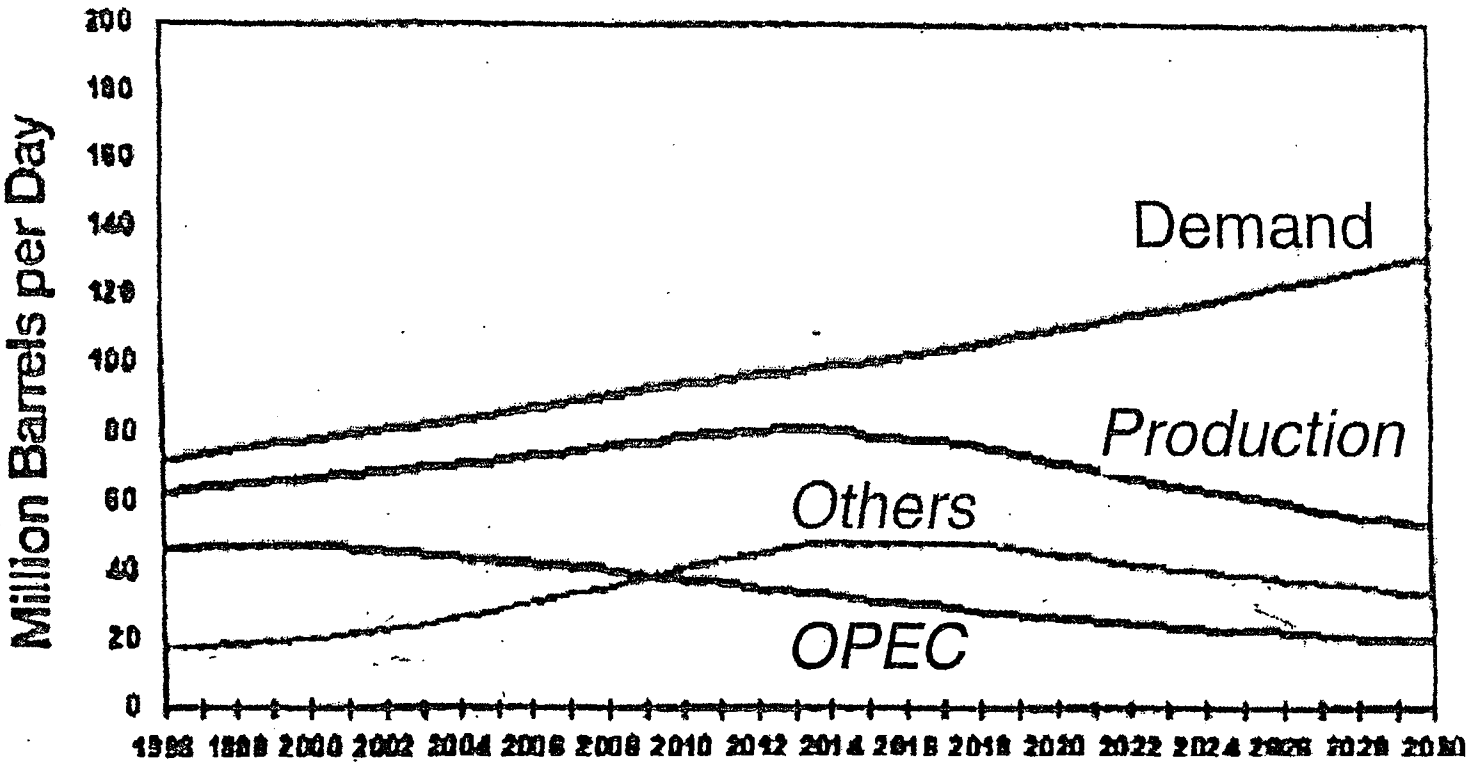
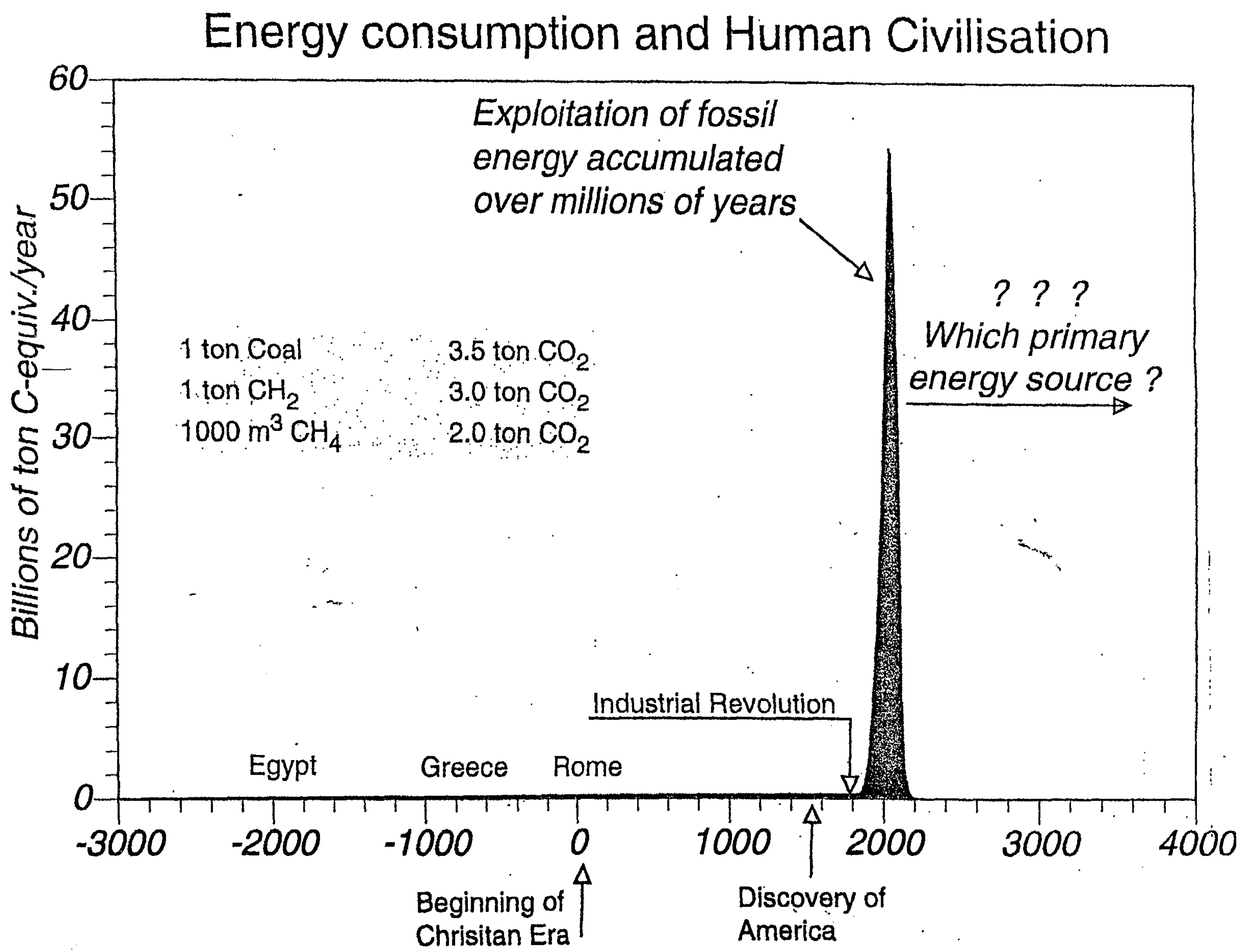

Primary energy input for the world, in MTCE
Million Ton Coal Equivalent
TeraWatt x year
Actual consumption
Constant rise: + 2.3 %/year
1000
100
10
10.0
1.0
0.1
1850
1900
1950
2000
Year
Kondratiev cycles for electric energy consumption in the US
Percent Deviation from exponential
USA Data
Electrical Energy
Total Energy
30
20
10
0
-10
-20
-30
1850
1900
1950
2000
Year

Figure 2

Figure 3.



The International Energy Agency projects a declining world conventional crude oil production (dark blue) after 2015. Graph also shows the global demand (red line), the oil production of the Middle Eastern OPEC countries (light blue) and that of other countries (green)



Energy consumption and Human Civilisation
Billions of ton C-equiv./year
60
50
40
30
20
10
0
Exploitation of fossil energy accumulated over millions of years
? ? ?
Which primary energy source ?
1 ton Coal	3.5 ton CO_2
1 ton CH_2	3.0 ton CO_2
1000 m^3 CH_4	2.0 ton CO_2
Industrial Revolution
Egypt
Greece
Rome
-3000
-2000
-1000
0
1000
2000
3000
4000
Beginning of Chrisitan Era
Discovery of America

Figure 4.

Energy prices,consumption and Substitution,All Synchronised

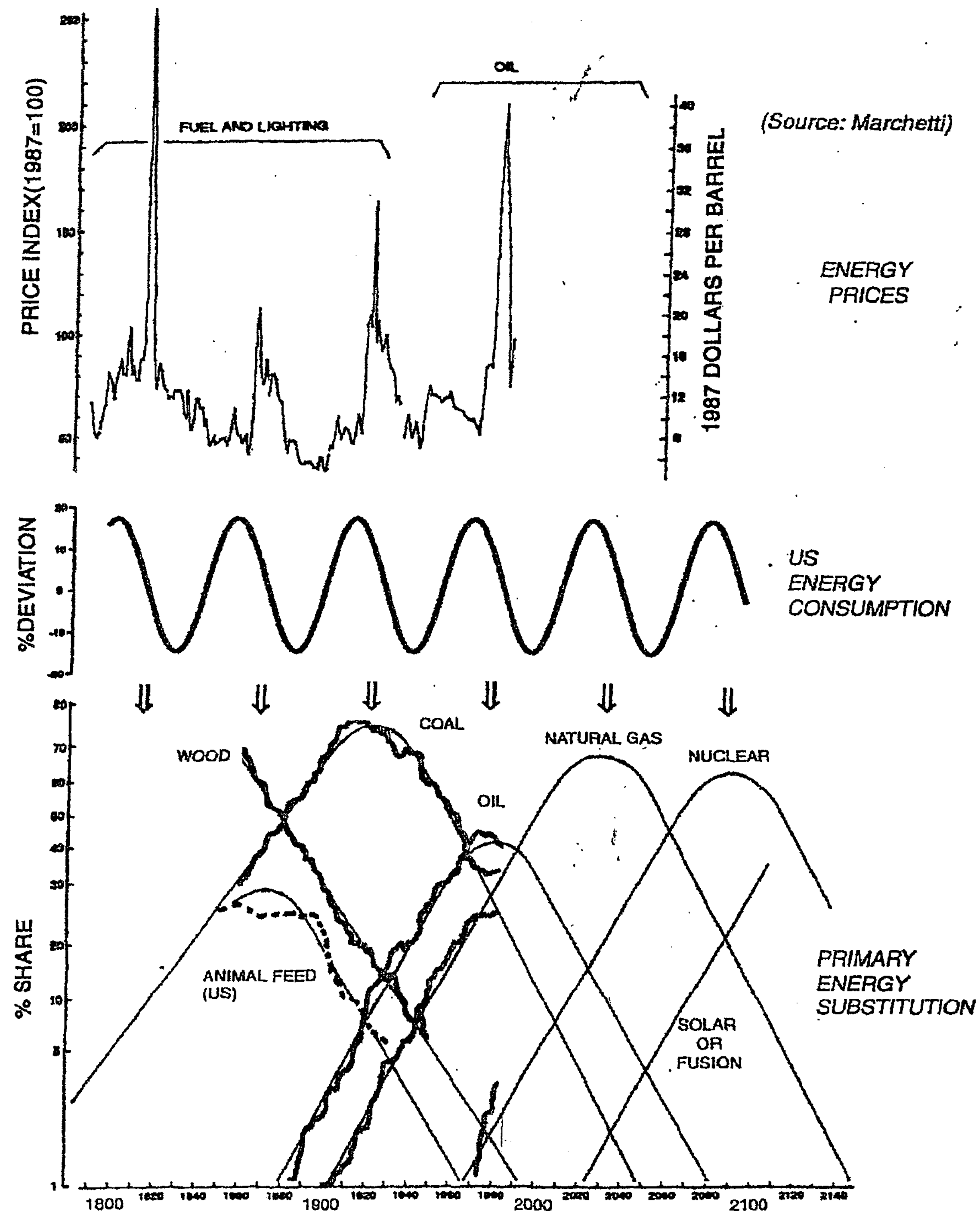
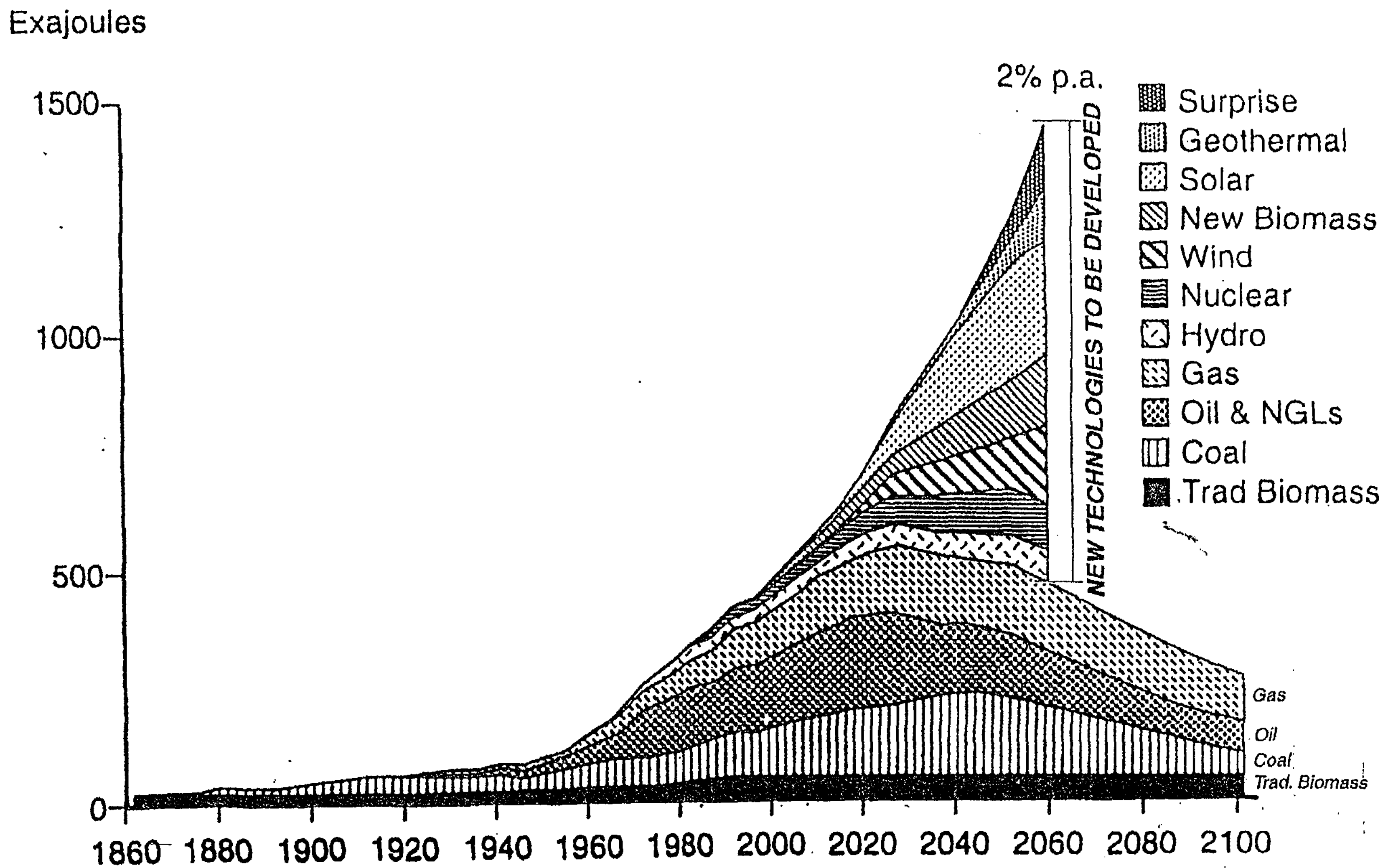


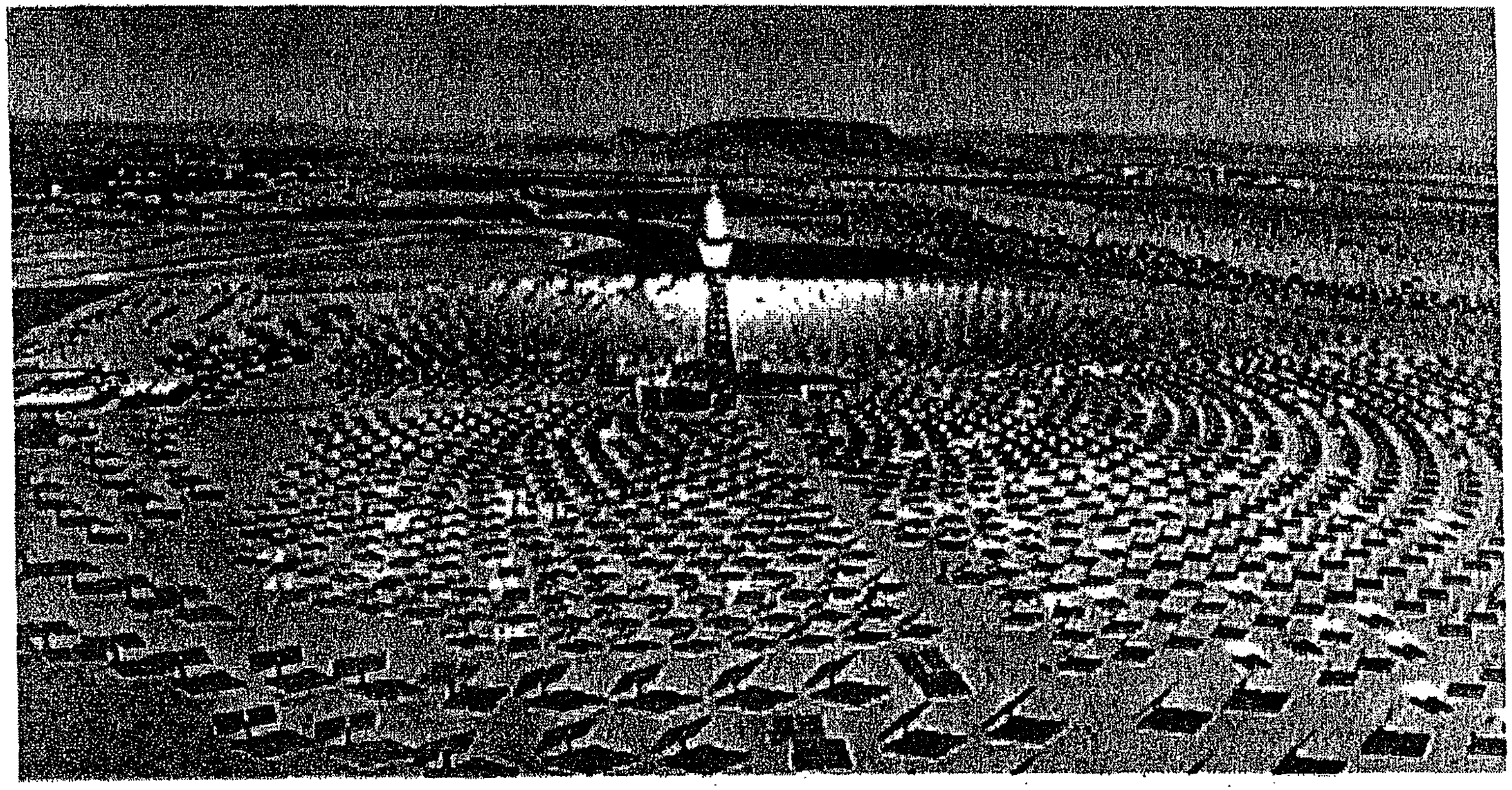
Figure 5.

Figure 6.



World Energy Use: Sustained growth 1860-2100. *Source:* Shell Group Planning PL/12.

10 MWe Solar Two power plant in operation



Temperature : 565 °C
Gross Thermal average power: 42 MWatt
Total collecting surface:100'000 m2

Rankine turbine power: 12.5 MWe
Steam : 100 bar @ 510 °C
Thermal storage:1500 tons of nitrate molten salt

Figure 7

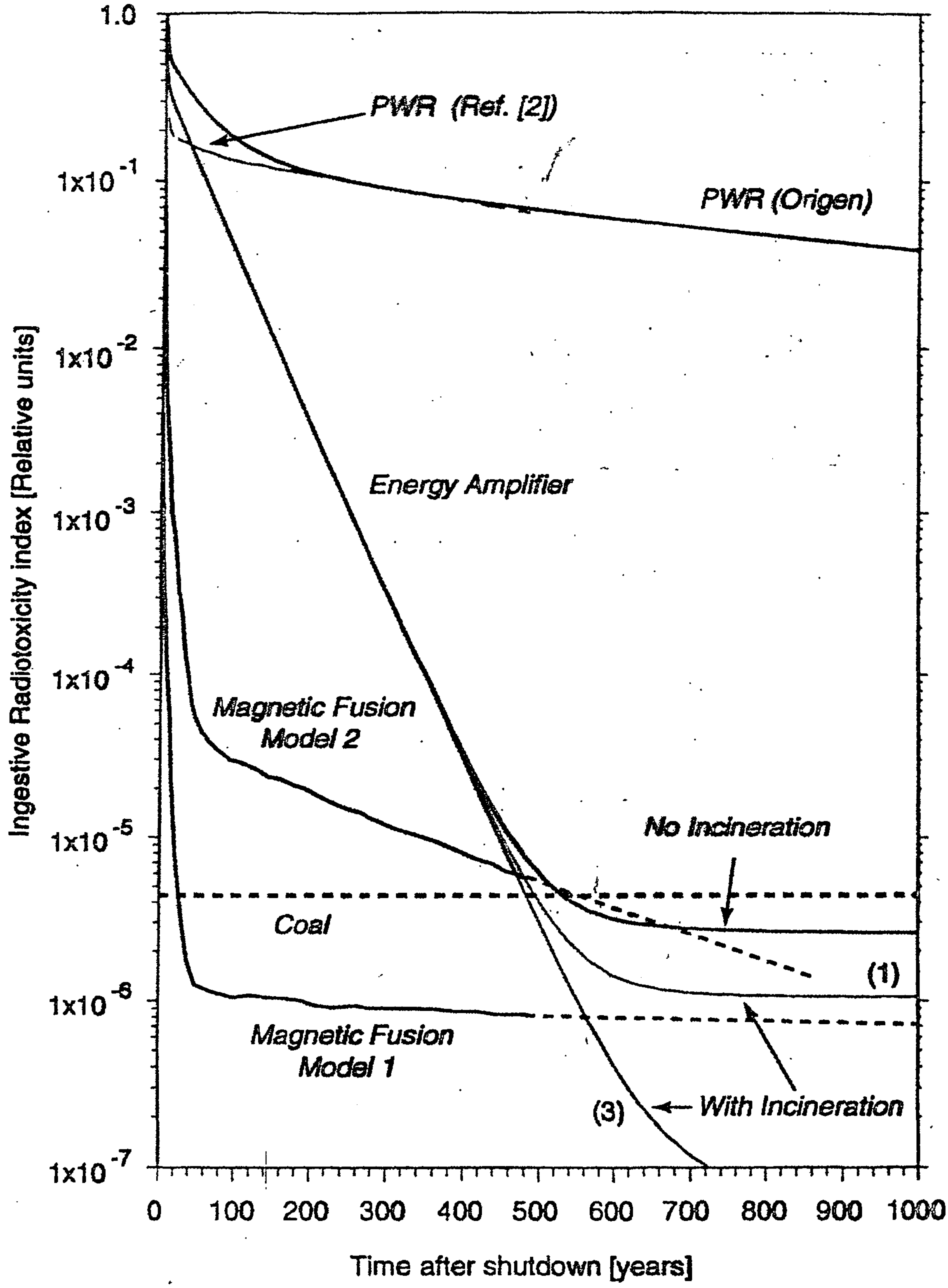

1.0
1x10^-1
1x10^-2
1x10^-3
1x10^-4
1x10^-5
1x10^-6
1x10^-7
Ingestive Radiotoxicity index [Relative units]
PWR (Ref. [2])
PWR (Origen)
Energy Amplifier
Magnetic Fusion Model 2
No Incineration
Coal
(1)
Magnetic Fusion Model 1
(3)
With Incineration
0
100
200
300
400
500
600
700
800
900
1000
Time after shutdown [years]

Figure 8.

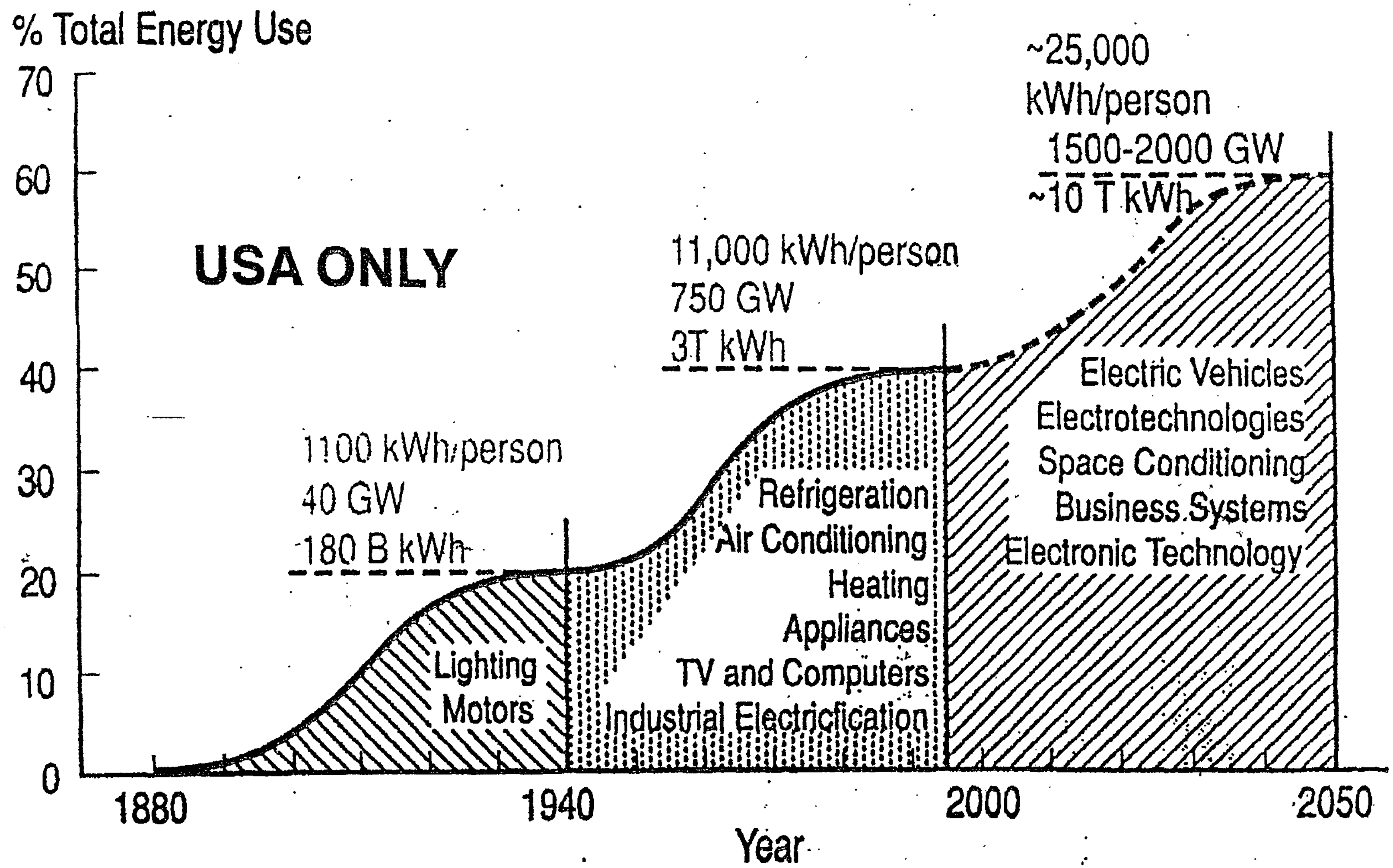

% Total Energy Use
70
60
50
40
30
20
10
0
USA ONLY
1100 kWh/person
40 GW
180 B kWh
11,000 kWh/person
750 GW
3T kWh
~25,000
kWh/person
1500-2000 GW
~10 T kWh
Lighting
Motors
Refrigeration
Air Conditioning
Heating
Appliances
TV and Computers
Industrial Electricfication
Electric Vehicles
Electrotechnologies
Space Conditioning
Business Systems
Electronic Technology
1880
1940
2000
2050
Year

Figure 9.