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Energy forecasting and atmospheric CO_2 perspectives: two worlds ignore each other

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Macroeconomic models predict that the global primary energy demand will increase by a factor of 2–4 by the year 2050. In contrast, climate analyses made by the IPCC claim that CO_2 emissions in 2050 should not exceed the values of 1990 or even be 20% lower. By 2100 emissions should be reduced to one third of the present value. The common wisdom to deal with these opposing trends is the concept of de-carbonization, i.e., the continuous decrease of the carbon emission per unit energy utilization. De-carbonization rates needed to compensate for the growing demand while keeping the CO_2-emissions constant should at least be 2% per year compared to actual values of 0.3%. The potential of different de-carbonization rate measures is analyzed. It is argued that the goal can only be met if per capita energy utilization in the industrialized countries is significantly reduced from their typical level of 5000–10 000 W. As a realistic target we suggest 2000 Watt per capita, the present global average. This would leave expansion capacity for the developing countries which presently have per capita demand between 300 and 1000 W. Based on the example of Switzerland it is shown that the two key issues to attain this goal are the quality of buildings and the demand for mobility. It is concluded that the conversion of the present energy system into a 2000 W system is neither limited by technology nor by finances but by the acceptance of a new life style in which energy is used more efficiently and more intelligently than today.

Keywords: global primary energy demand, CO_2 emission, climate, de-carbonization, per capita energy utilization, 2000 Watt Society, sustainable energy use

1. Energy – a key issue of modern society

Energy has never been so cheap and abundant in history as in 1998 and it is still fairly cheap today. Doomsday predictions, which have been popular since the Club of Rome first published its famous book "Limits to Growth" about 30 years ago, seem to be ridiculed by the economic reality. Yet, simple numerical considerations demonstrate that in the long run the global energy system – if extrapolated into the future – will severely collide with the conditions of sustainable development (see box below).

Sustainable development

The expression "sustainable development" owes its present popularity to the 1987 report of the Commission on Environment and Development ("Brundtland Commission") where it was defined as a global development which can meet today's needs without jeopardizing the needs of future generations. The requirements of sustainability are often discussed in terms of ecological, economical and societal aspects. However, sustainable development also includes a *spatial* dimension (i.e., meet the needs of a particular country without jeopardizing the needs of others). In its strictest interpretation, sustainable development would mean to completely abandon the use of non-renewable resources, e.g., coal, oil and natural gas. According to a more moderate view, the use of non-renewable resources is not excluded as long as technical progress provides substitutes and new resources at a pace exceeding the exploitation of existing resources.

In other words: although the present price signal reflects the availability of abundant energy today, it neither takes into account the growing needs of the billions of people with a per capita energy utilization well below the level necessary for a decent existence, nor does it consider the consequences of the substantial global population growth. On the one hand, the problem which we eventually face may still be decades away (this explains why price signals do not work); on the other hand it will take at least two generations to significantly alter the energy dependence of modern society.

Mankind is confronted with an intriguing question: is it possible to intellectually anticipate a problem and to act accordingly well before the political and economical signals show unambiguous evidence of that problem? Can the scientific community, together with the economic sector, launch a long-term program based on a question which most people do not (yet) recognize as being important?

Presently, society witnesses two kinds of energy perspectives. On the one hand, international organisations such as the OECD (e.g. [1]), the International Energy Agency (IEA) [2] or the International Institute for Applied Systems Analysis (IIASA) (e.g. [3]) use macroeconomic models to show that the global energy utilization will increase by at least a factor of three until the year 2050. Most of this increase would be taken up by fossil fuels. These models claim that the growing demand is system-inherent and any attempt to interfere with the energy system would cause enormous economic damage. In contrast, climate models developed in the framework of IPCC predict that, if atmospheric CO_2 concentrations should not exceed a level 60% above the pre-industrialization value, total CO_2 emissions had to be reduced to the level of 1990 or even below by the year 2050 and to about one third of the 1990 emissions by the end of the 21st century.

It is tacitly assumed that the gap between these opposing perspectives has to be (and will be) bridged by a set of measures named "de-carbonization" of the energy system, i.e., by the decrease of carbon emissions per unit primary energy utilization. This includes both the shift to fossil fuels with smaller CO_2-production/energy gain ratios (e.g., a shift from coal to oil and gas) as well as the accelerated development of renewable energy technologies (hydro, solar of all kinds, wind, geothermal, waste and biomass). In some scenarios nuclear energy also plays an essential role in the future energy mix. Present de-carbonization rates are approximately 0.3% per year [4].

As the principal message of this article it will be shown that these expectations are built on weak ground. Either the present trend to supply the major fraction of the commercial energy demand from fossil fuels will be continued far into the 21st century (in spite of IPCCs plea for reducing the output of greenhouse gases), or our financial and innovative efforts are radically shifted toward measures to conserve energy and to use it more intelligently. Such an effort would have to turn the predicted three-fold increase of the global energy demand into a curious phantom of the present modeling culture in which trends are extrapolated into the future leaving only little room to real innovation. It is argued that it will not be possible to substitute fast enough fossil resources by renewable ones as long as the global energy demand increases by 2.2% per year (the value underlying the mentioned macroeconomic prediction which triples the total needs within 50 years). Energy scenarios which tacitly combine de-carbonization rates with the conventional energy growth scenarios are meant to eventually fail.

A quick glance at present rates of change can provide some first evidence for this argument: If within the next 50 years total energy demand will triple while the CO_2 output should remain constant or even decrease by about 20% compared to its present value, a total de-carbonization factor of 3 or more would be needed during this period, i.e., equal to the average energy demand increase (2.2% per year). This contrasts with the present rate of 0.3% per year [4]. In fact, the latter rate would just lead to a total de-carbonization factor of 1.16. Thus, in the year 2050, when the total primary energy demand is said to be three times larger than today, the CO_2 output would be at a level of $(3/1.16) = 2.6$ of today's value, i.e., rise by 1.9% annually. As a consequence, atmospheric CO_2 concentrations would reach values well above 500 ppm in 2050 and continue to grow to values two to three times larger than the pre-industralization value of about 280 ppm.

In the following we first give a brief summary of the present global energy. The next two sections deal with two kinds of models, the macroeconomic energy models which, based on demographic and economic parameters, forecast future demands, and the climate models used by the IPCC to predict and assess the consequences of different atmospheric CO_2-input scenarios. A further section discusses alternative energy paths into the future, especially for OECD countries like Switzerland, and evaluates them in terms of the requirements of sustainability. Special emphasis will be put on the scenario for a more effective use of energy. Summary and conclusions are given in the final section.

2. The world energy system and sustainability

Reported quantitative information on the world energy system varies between different sources. One reason is that different definitions and conventions are used for technical terms such as "primary energy" and "final energy". Furthermore, reliable information is missing on the use of traditional (non-commercial) energy resources such as fire wood, animal waste and others, especially from developing countries where non-commercial energies often are by far the largest energy source.

Yet, for the following arguments minor numerical differences in these values do not really matter as long as it is made clear how the different numbers are defined. It turns out that for the term "primary energy" the following convention serves our purpose best:

Primary energy

Primary energy of *fuels* (fossil or recent) is calculated from the lower heating value (LHV) of the fuel, i.e., from the chemical energy relative to the oxidation of the fuel but neglecting the energy of condensation of the water vapor produced by combustion. This value is used whether the heat content of the fuel is used directly (e.g., for heating) or for the production of other forms of energy (especially electricity). Primary energy of *resources which are solely used for electricity production* (nuclear, hydropower, wind, photovoltaic and others) are accounted for by the electric energy produced at the plant. Thus, in contrast to the World Energy Commission and others, we do *not* convert nuclear and hydropower into primary thermal equivalent energy with one or different conversion factors. Finally, the use of ambient heat or radiation by passive solar architecture, by solar heat cells, by heat pumps, etc., is *not* counted as primary energy. We are aware of the fact that the use of renewable energy is often accompanied by the use of conventional energy (e.g., for the construction of passive solar buildings, insulation material, etc.), but these energies are included in the figures reported for conventional energies in the energy statistics.

Our starting point are the values for the global energy utilization in 1993 reported by the International Energy Agency [2]. Where necessary these values are adapted according to the above definition of "primary energy" and listed in table 1.

The total global commercial energy utilization of 323 EJ/yr (EJ = Exajoule = 10^{18} Joule) is predominantly supplied by fossil fuels. This remains true even when taking into account that the value listed as "solids" also includes the energetic use of biomass in OECD countries. Nuclear and hydroelectric power each add about 2.5% leaving just a very small fraction to alternative resources. Note that if nuclear and hydroelectric power were given as thermal energy equivalents with an average efficiency factor of 38.5%,

Table 1
Yearly global commercial energy utilization (1993).[a]

	Primary energy		Final energy (EJ/yr)	
	(EJ/yr)	(%)	Electricity	Other
Solids[b]	96	29.7	17.2	38
Oil	137	42.4	4.4	109
Gas	72	22.3	6.7	42
Nuclear	7.9[c]	2.4	7.9	–
Hydro	8.6[c]	2.7	8.6	–
Others	1.5	0.5	1.5	–
Total	323	100	46 (20%)	189 (80%)
Total final energy			235 EJ	72.7%
Transformation and other losses			88 EJ[d]	27.3%

[a] Adapted from IEA [2] (EJ = Exajoule = 10^{18} Joule).

[b] Includes biomass used as energy resource in OECD countries, but not in non-OECD countries.

[c] Primary energy defined as electricity production.

[d] Does not include waste heat of nuclear power plants and conversion loss of potential energy into electricity at hydroelectric power stations.

the corresponding primary energies would rise to 20.5 and 22.3 EJ/yr. There relative contribution to the total supply of primary energy would then be 5.8 and 6.4%, respectively.

Slightly more than one fourth of the primary energy is lost during its transformation into final energy. Half of this loss is waste heat, the by-product of the production of electricity in fossil thermal power plants. One fifth of the final energy is consumed as electricity. Note that the contribution of nuclear and hydropower to electricity is 17 and 19%, respectively, thus these resources, although being negligible for total energy demand, contribute more than one third to electricity.

Given a world population of about 5.5 billion people in 1993, the average energy utilization per capita is 59 GJ/yr (GJ = 10^9 Joule). Expressed as a continuous energy flow the per capita energy utilization corresponds to an average power of 1 860 W (see box).

Energy and Power: Joule and Watt

Energy as a quantity is expressed in Joule (J) or in kilowatt-hour (kWh). The flux or utilization of energy per unit time is called power and expressed in Watt defined as 1 Watt = 1 Joule per second. Kilowatt-hour per day or per year can also be used as power units. The total global energy utilization in 1993 of 345 EJ/yr (taken from table 2, see below) corresponds to the mean power of 11 TW = 11×10^{12} W.

2000 W corresponds to an energy flux of:

- 2000 Joule per second, *or*
- 48 kilowatt-hour per day, *or*
- 17 500 kilowatt-hour per year, *or*
- the consumption of about 1700 liter of heating oil or gasoline per year.

Table 2
Total (commercial and traditional) global energy utilization (1993) – some typical values.[a]

	Total (EJ/yr)[b]	Non commercial[c] (% of total)	Per capita (total) (Watt p.c.)[d]	Per capita (% change since 1973)
World	345	6.1[e]	2000	6
Africa	13.6	35	630	27
Ethiopia	0.46	90	290	
Nigeria	1.7	59	530	92
Asia	105	9	970	84
Japan	17.5	$\sim$0	4500	24
China	31.7	6	850	104
India	12.1	23	420	100
Sri Lanka	0.17	53	290	10
Europe	110	<1	4700	73
United States	82.7	1	10 200	−7
Canada	9.3	<1	10 200	12

[a] From *World Resources 1996/97*.

[b] 1 EJ = 1 Exajoule = 10^{18} Joule.

[c] Traditional fuels such as fire wood, animal waste, etc.

[d] 1 Watt = 1 Joule per second.

[e] Estimates of the global consumption of traditional energy fuels vary between 6% and more than 10%.

The values given in table 1 do not include the use of non-commercial energy resources which in many developing countries make up the major energy source, especially as biomass (fire wood, animal manure, etc.), but also as the physical power of humans and animals. Reliable statistical data are scarce. This explains why estimates for the relative contribution of traditional fuels to primary energy differ between 6% and more than 10%.

Table 2 gives numbers for total (commercial and traditional) primary energy utilization for some continents and countries. According to this compilation the average contribution of non-commercial to total energy is 6%, thus the absolute total energy utilization should be 6% larger than the value given in table 1. Although tables 1 and 2 are constructed from different sources the values are indeed fairly consistent. Note that the global mean total (commercial and non-commercial) primary energy utilization per capita corresponds to 2000 W.

Two characteristic features can be extracted from table 2: first, the mean energy demand per capita calculated for different countries strongly varies between developing and industrialized countries. Second, the relative contribution of non-commercial energies is very small in countries with per capita demand of more than 1000 W. In contrast, in countries with extremely small energy demand non-commercial energy represents a significant fraction of the energy demand – in some cases such as Ethiopia even the major fraction.

In the last 50 years the global energy system has undergone fast changes (figure 1): the global commercial energy demand increased from 76 EJ/yr in 1950 to 311 EJ/yr in 1992, that is by the factor 4.1. or – on the average – by 3.4% annually. This extremely fast growth of the global energy demand was only possible due to the enormous capacity of the emerging oil industry followed by the development of gas fields. As a result, the relative share of oil and gas grew from 16% in 1950 to 66% in 1992.

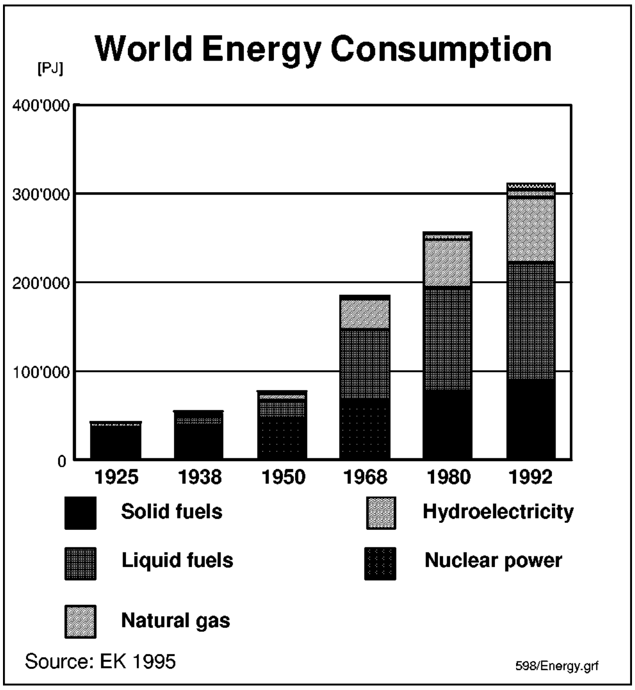

Figure 1. Temporal development of annual global utilization of commercial energy between 1925 and 1992. 1 PJ = 1 Petajoule = 10^{15} Joule. Hydropower and nuclear power are calculated as primary energy. From [5,6].

During the first half of the post-war period, i.e., between 1950 and 1970, the global mean annual growth rates of population and commercial energy utilization were 1.8 and 4.8%, respectively, thus giving rise to a considerable growth of the energy use per capita from 950 to 1700 Watt per capita. This development was accompanied by a continuous shift away from renewable resources (mainly biomass and hydropower) to fossil fuels Yet, as the numbers given in table 2 show the increase of individual energy utilization was significantly levelled off after 1970. Between 1973 and 1993, the total (commercial and traditional) energy use per capita rose by merely 6% (0.3% annually). In contrast, during this period the world population grew by 1.7% per year. Although in some developing countries the growth rates of per capita energy use were significantly larger, there are many others with negative growth. In some industrialized countries there are signs that the energy demand is approaching saturation.

In essence, the development of the global energy system *during the last twenty years* are characterized by the following observations:

(1) Most of the increase of the global energy demand was due to population growth; the global mean per capita energy utilization grew only slightly.

(2) The growing energy demand is predominantly satisfied by fossil resources.

(3) The present energy system is inherently linked to the increase of atmospheric CO_2 and thus to the potential perturbation of the globe by climatic changes.

(4) The average per capita energy utilization varies by more than a factor of 20 between industrialized and developing countries. If commercial energy alone is considered, the gap between the rich and the poor exceeds the factor 3.

(5) Although the final reserves of fossil energies are not yet considered as important economic restrictions, the discrepancy between the geographical distribution of the major oil and gas resources and the present distribution of energy demand represents a latent danger to the stability of the global economic system.

We conclude that the present global energy system is not sustainable, neither regarding the temporal aspect of sustainability (future generations) nor the geographical one. The main reasons are the strong dependence on non-renewable resources, the threat of climate change linked to the burning of fossil fuels, and the immense gap between the rich and the poor nations.

Of course, this analysis does not come as a big surprise. In fact, the interesting point is not the actual non-sustainability of the energy system, but the question whether the present trends are moving the energy system closer to sustainability or away from it. In order to try an answer we have to look at the information produced by models which predict the development of the global energy system in the decades to come.

3. Predictions of the global energy system

It is not intended to present a thorough overview of the rich selection of energy forecast models and to discuss in detail their differences hidden in the underlying assumptions made by the various authors. In fact, most models have in common that they are based on macroeconomic considerations, i.e., on assumptions regarding factors such as population and economic growth as well as key parameters reflecting technological and institutional changes.

For the argumentation pursued in this article it will be sufficient to discuss just two groups of models. The first is the one by the World Energy Council (WEC) published in 1993 [7]. The study is the result of an interactive bottom-up and top-down process combining global views with the results achieved by nine regional groups which analyzed their regional energy issues and requirements. Three scenarios are developed in a qualitative manner with the intention to illustrate future possibilities, but *not* to predict the future. None of the scenario represents a business-as-usual case. The scenarios are:

case A – high growth,

case B – moderate growth,

case C – ecologically driven.

The population growth taken from the current UN projection is assumed to be the same in all cases. It implies

Table 3
Basic assumption and forecast of WEC model [7].

Case	A high growth	B moderate growth	C ecologically driven
GDP growth rate, k_{GDP} (%/yr)			
World	3.8	3.3	3.3
OECD	2.4	2.4	2.4
DC	5.6	4.6	4.6
Energy intensity growth rate, k_{EI} (%/yr)			
World	−1.6	−1.3	−2.4
OECD	−1.8	−1.9	−2.8
DC	−1.3	−0.8	−2.1
Combined rate, $k_{\mathrm{GDP}} + k_{\mathrm{EI}}$ (%/yr)			
World	2.2	2.0	0.9
OECD	0.6	0.5	−0.4
DC	4.3	3.8	2.5
Relative increase of primary energy demand from 1990 to 2020			
World	1.93	1.82	1.31
OECD	1.20	1.16	0.89
DC	3.63	3.13	2.12
Relative change of primary energy demand per capita (1990 to 2020)			
World[a]	1.26	1.19	0.86
Extrapolation into year 2050 Relative increase of primary energy demand from 1990 to 2050			
World, total	3.7	3.3	1.7
World, per capita	2.0	1.7	0.9

[a] Assumption for world population: 1990 5.3 billion, 2020 8.1 billion, 2050 10 billion.

an increase in world population from 5.3 billion in 1990 to 8.1 billion in 2020, the time horizon of the WEC-analysis. Further projections of the population are 10 billion in 2050 and 12 billion in 2100.

The applied method is extremely simple and thus easy to reproduce. The global primary energy utilization in the year 2020, $G(2020)$ is calculated from the equation

$$G(2020) = G(1990)\exp\bigl[30(k_{\mathrm{GDP}} + k_{\mathrm{EI}})\bigr], \qquad (1)$$

where k_{GDP} and k_{EI} are annual growth rates of the global domestic product (GDP) and energy intensity, respectively, and $G(1990)$ is energy utilization in 1990. Energy intensity is defined as primary energy utilization per real gross domestic product expressed, e.g., in PJ per US\$. Often the term “energy efficiency” is used for the inverse number (US\$ per PJ). Table 3 summarizes the k-parameters used in the WEC models. Just two extreme groups of nations, OECD countries and developing countries (DC), are shown in the table together with average k-values for the world as a whole.

In the model all GDP growth rates are assumed to be positive, but they strongly vary between the scenarios and regions. The largest rate is chosen for the DC group for case A (5.6%/yr), the smallest for the OECD countries in all cases (2.4%/yr). In contrast, energy intensities are assumed to decrease in all regions and all scenarios. Obviously, the largest negative k_{EI}-values are found in case C (−2.8%/yr for OECD). Yet, the combined rate, $k_{\mathrm{GDP}} + k_{\mathrm{EI}}$, which according to equation (1) determines the sign of the change of G, is negative for only one case, i.e., for the OECD countries in case C. As a consequence, according to this scenario the primary energy demand of the OECD countries would decrease by 11% from 1990 to 2020. As shown in table 3, in all other cases an increase of G is expected. For the world as a whole the relative increase varies between the factor 1.93 (case A) and 1.31 (case C). The largest relative increase is 3.63 (DC group, case A), but even in the ecologically driven case energy demand in the DC group is assumed to grow by the factor 2.12 from 1990 to 2020. Most of this increase is due to population growth, as can be seen by the modest relative change of per capita energy utilization. For case C the latter would even decrease by 14% from 1990 to 2020.

Although the WEC models were not meant to be extrapolated over another 30 years into the future, we have added the relative changes of both the total global energy demand and the per capita demand between 1990 and 2050 in table 3 in order to show where the underlying assumptions would eventually lead to. The absolute changes are between 3.7 (case A) and 1.7 (case C), the per capita changes between 2.0 (A) and 0.9 (C). For cases A and B the growth of energy demand would be caused by both population growth and growth of per capita demand. In contrast, in the ecologically driven case per capita energy utilization would slightly decrease (factor 0.9).

Obviously, it is dangerous to assume that the trends adopted for the period 1990–2020 should remain unchanged for another 30 years. Therefore, the speculative results presented in the last two lines of table 3 will be compared with the analysis published by the OECD [1] which was explicitly extended to the year 2050 (figure 2). In this representation the subdivision into regions is less detailed than in the WEC-study; the curves represent the world as a whole, the OECD plus “Economy in Transition” (EIT) countries, and the rest of the world.

The OECD model roughly corresponds to a situation between case B and C of the WEC scenarios. The assumed population development is approximately equal. Energy efficiency, the inverse of energy intensity, increases by the factor 3.6 in 60 years which corresponds to an average annual rate of change of 2.1% (or −2.1% for energy intensity). This value is slightly smaller than in case C, but significantly larger than in case B. Total primary energy demand grows by the factor 2.8 (1.7% per year), but the per capita energy demand grows only by 1.7 to about 110 GJ/yr or roughly 3500 W.

If these numbers are analyzed separately for the OECD/EIT states and the others, it appears that although relative growth in the latter (factor 2.5 or 1.5% annually) is larger than in the former (factor 1.8 or 1.0% annually), the absolute gap between the rich and the poor countries still increases. At first sight it might be confusing that the ratio between the 2050 and 1990 per capita utilization for the

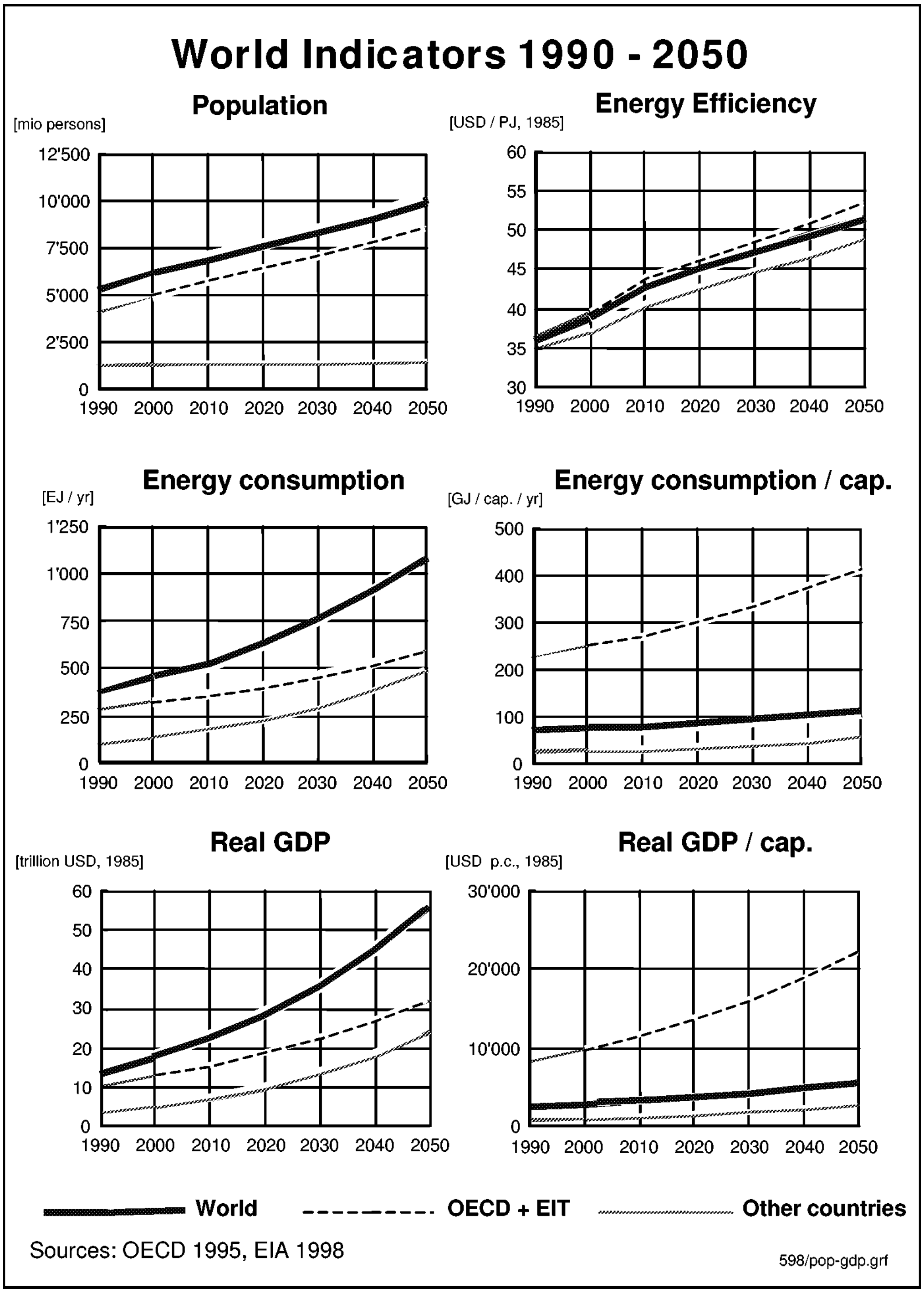

Figure 2. World indicators 1990–2050. Real GDP = global gross domestic product based on price index of 1985. EIT = economies in transition (former Soviet Union member states). From [1,6].

world (1.7) is smaller than both the ratio for the OECD/EIT states (1.8) and the others (2.5). However, one has to take into account that the fraction of the population living in these other countries (where per capita energy utilization is small) will be much larger in the year 2050 than today (see figure 2). The corresponding decrease of the average per capita demand is only partially compensated for by the individual increase of energy utilization. According to the model average per capita demand will be about 13 000 W in the OECD/EIT states and 1900 W in the developing world.

To summarize the lesson told by these models, it seems that absolute energy demand will double or even triple by the year 2050 compared to 1990. For the ecologically driven scenario the total increase is only 1.7. This model is unique in the sense that per capita demand in the industrialized countries would remain stable or even slightly decrease to leave room for the urgently needed additional per capita energy in the developing countries.

Table 4
The global CO_2 situation.

CO_2 emission per capita and year		
World average	4	t CO_2 p.c. and year
USA	21	
OECD countries	12	
India	0.7	

Total CO_2 emission (Gt CO_2/yr)

	1992	2050	2100
Actual	23		
OECD scenario		67	
WEC case A		50	56
WEC case B		41	40
WEC case C		25	8.4
IPCC scenario S450		16–22[a]	8

Permitted CO_2 emission per person and year for S450 scenario

	Population (10^9)	Emission per capita (t CO_2/yr)	Potential energy production from[b] (Watt per person) Coal	Oil	Gas
2050	10	2 (1.6–2.2)	700	900	1100
2100	12	0.7	200	300	400
After 2200	∼12	0.3	<100	<130	<170

[a] Different temporal pathways lead to different tolerated emission rates in 2050; yet, the tolerable long-term emissions are independent of the pathway [9].

[b] Calculated with the following CO_2 emission factors [10]: coal 94.5, crude oil 73.3, natural gas 56.1 (values in kg CO_2/GJ).

4. Atmospheric CO_2 and its impact on global climate

The question arises how the additional energy demand predicted by the traditional energy models will be covered. When looking backwards (figure 1) it becomes evident that the spectacular increase of energy utilization in the past has only been possible thanks to the abundant and cheap availability of fossil fuels. The known reserves will still hold for several hundred years, especially if coal became more important again. The real problems are waiting elsewhere, i.e., in the political situation caused by the geographical distribution of the major oil and gas reserves on one hand and in the atmosphere on the other hand.

Here it is not the place to discuss the first point. Instead, we will analyze the restrictions imposed by the dynamics of the global carbon cycle on the use of fossil fuels. As for the economic sector, predictions can only be made based on mathematical models. While it is still relatively easy (although by no means trivial) to predict future atmospheric CO_2 concentrations, it is much more complicated to forecast their implication for the global or local climate. Again, for the sake of the argument, we will simplify the situation as much as possible by basing the following discussion on the models employed by the IPCC [8] in which the atmospheric CO_2 concentration, C, is related to the temporal change of the anthropogenic CO_2 emission, $J(t)$. Among the different cases we choose the “S450” scenario in which C reaches 450 ppm (about 60% above the pre-industrialization level of 280 ppm) some when towards the end of the 21st century. Although this is the most stringent case among the scenarios analyzed by the IPCC, it is by no means overprudent as the corresponding predictions on possible climatic changes portrayed by the IPCC reports demonstrate. Yet, it should be noted that the 560 ppm scenario (twice pre-industrial level) is now often used as a realistic target.

A summary of the global CO_2 situation is given in table 4. The figures indicate the growing gap between the emissions predicted by the OECD and similar models on one hand, and the boundary conditions imposed by the climate issue on the other hand. For the year 2050, the OECD model predicts a global emission of 67 Gt/yr. Emissions for the WEC-scenarios vary between 50 Gt/yr (case A) and 25 Gt/yr (case C). The latter is not far from the tolerated emission calculated for the IPCC scenario S450 which lies between 16 and 22 Gt/yr. The WEC study includes rough estimates for CO_2 emissions in the year 2100. It is evident that for cases A and B the gap between real and tolerated emission becomes even larger. Case C comes close to the emission curve requested by the S450 scenario.

Table 4 also gives the potential average energy production per person which would be in accordance with the limits of the S450 scenario. Due to the different CO_2 emission factors of coal, oil and gas, these values vary between 700 and 1100 Watt per person in the year 2050 and between 200 and 400 W in 2100. Whether coal or gas would be the future fossil basis (the former is more probable on the long run, since the reserves of oil and gas are significantly smaller than the reserves of coal), all these numbers would mean a significant reduction in the use of fossil fuels relative to the present energy mix. This strongly conflicts with the energy models which all predict a large increase of fossil fuel utilization.

There are two main paths leading out of the dilemma. Either measures can be found to make the predicted increase of the global energy demand untrue, or it is possible to decouple the anthropogenic flux of carbon to the atmosphere from energy utilization, a process called de-carbonization. The CO_2 intensity of the global energy system, κ, is defined as

$$\kappa = \frac{J}{G} \quad (\mathrm{Mt\ CO_2/EJ}), \tag{2}$$

where J is the annual anthropogenic CO_2 flux to the atmosphere and G is the annual global primary energy utilization.

The de-carbonization rate is defined by

$$k_\kappa = -\frac{1}{\kappa}\frac{\mathrm{d}\kappa}{\mathrm{d}t} = k_G - k_J \quad (\mathrm{yr}^{-1}), \tag{3}$$

where k_G and k_J are the relative rate of changes of primary energy utilization and atmospheric CO_2 flux, respectively:

$$k_G = \frac{1}{G}\frac{\mathrm{d}G}{\mathrm{d}t}, \qquad k_J = \frac{1}{J}\frac{\mathrm{d}J}{\mathrm{d}t} \quad (\mathrm{yr}^{-1}). \tag{4}$$

Table 5

Influence of different measures on global commercial primary energy utilization G and on CO_2 intensity κ.

	Relative de-carbonization rate (k_κ/k_{sub})	Maximum theor. emission reduct. of CO_2, ΔJ_{max} (Mt CO_2/yr)	% of current CO_2 emission, J	Maximum theor. effect on primary energy demand, G (EJ/yr)
1. Substitution fossils by fossils				
coal → oil	0.088	−2000	−8.8	–
coal → gas	0.16	−3700	−16	–
oil → gas	0.10	−2300	−10	–
2. Substitution of fossil produced electricity by renewable or nuclear resources				
replacement of coal plant	0.10	−1600	−7	−28
replacement of oil plant	0.059	−300	−1.4	−7
replacement of gas plant	0.024	−400	−1.6	−11
3. Use of waste heat from thermal electric power plant to replace[a]				
coal	0.036	−3400	−15	−17.2
oil	0.0024	−2600	−11	−4.4
gas	−0.024	−2000	−8.6	−6.7

[a] It is assumed that the maximum use of waste heat is equal to the electric power output. This leaves another 25% of the total thermal power production as transformation and transport losses.

Calculations based on the figures from table 1.

F_i consumption of fossil fuel i (coal, oil, gas) in EJ/yr

γ_i relative contribution of fossil fuel i to total primary energy use

ε_i CO_2 emission factor of fossil fuel i (from [10])

J_i CO_2 emission from fossil fuel i (J: total emission per year)

	F_i (EJ/yr)	γ_i	ε_i (Mt CO_2/EJ)	J_i (Mt CO_2/yr)
Coal	96	0.297	94.6	9080
Oil	137	0.424	73.3	10 040
Gas	72	0.223	56.1	4040
Total	305	0.944	weighted av. 75.9	$J = 23\,160$

In table 5 the de-carbonization rates of different possible measures are analyzed. They are: (1) the substitution of a fossil fuel by another fossil fuel with a smaller CO_2-emission factor (e.g., coal by oil or gas); (2) the substitution of fossil produced electricity by renewable or nuclear electricity; (3) the substitution of fossil based heat production by the use of waste heat from thermal electric power plants or by the co-generation of heat and electricity. The de-carbonization rates are given relative to the corresponding substitution rates k_{sub}. For instance, for the case of the substitution of coal by oil, k_{sub} is given by

$$k_{sub} = \frac{1}{F_{coal}} \frac{dF_{coal}}{dt}, \qquad (5)$$

where F_{coal} is the present consumption of coal in EJ/yr (table 1). According to table 5 the resulting de-carbonization rate k_κ is 8.8% of the coal substitution rate k_{sub}.

Significant carbon emission reductions and maximum effects on primary energy which are also listed in table 5 indicate the potential integrated effect of the corresponding substitution if it were fully realized. Although these theoretical potentials are large (see, e.g., the coal/gas substitution with a theoretical CO_2-reduction potential of 16% of present emissions or the use of waste heat with an even larger potential), they quickly reach severe technical and economic limits.

From equation (3) we conclude that in order to compensate for the predicted rates of change of G (2.2% per year), the sum of the de-carbonization rate resulting from the combination of several measures would have to be at least 2.2% per year if J were to remain constant ($k_J = 0$). It is not clear how this target could be met.

Yet, the situation would gain considerable flexibility if de-carbonization were not the only recipe to meet the carbon emission goal. If the growth of G could be reduced, the requirement upon the de-carbonization rate would be lessened.

5. Alternative paths into the future

Over a time scale of several generations the solar energy flux will be the most probable basis for the energy system of man. As discussed by Imboden and Jaeger [6] in greater detail, there are only two other alternatives, the continuation of the fossil option and the build-up of a nuclear pathway. Without any doubt the former is extremely tempting: Prices are (still) rather low, the reserves are large and the necessary investments to increase output small compared to other options. Thus, there exists a considerable probability that – in spite of IPCC – fossil energy will still dominate our energy system in 2050 and thereafter.

The nuclear option would be *technically* feasible, but it would not be compatible with a world which is neither stable nor peaceful. The unsolved question of nuclear waste disposal and the problem of nonprofileration makes the globe dotted with 1600 power plants (compared to today's number of about 400) not very attractive. This number would be needed just to produce the present demand for electricity (46 EJ/yr) by nuclear power alone. Today, nuclear energy contributes only 17% to the total electricity production, and electricity is only 20% of the total final energy utilization. Thus, if nuclear power were to take over the present role of fossil fuels (and that in a world with growing demands), several thousands of nuclear power plants would have to be built in the next 50 years. Nobody really believes that this will happen.

So, we remain with solar energy. Its present contribution is still extremely small, production still expensive (especially for electric power by photovoltaic cells). Solar power needs time, and it will hardly be able to keep its present relative share if the global energy demand increases by 2% per year.

But there is a technology (or rather a set of technologies) already at hand which has the potential to avoid the overshooting of atmospheric carbon dioxide: the rational use of energy. In fact, an industrialized country like Switzerland could enjoy its present standard of living at a significantly reduce level of energy utilization. No new technologies would be needed to achieve that goal, although new technologies would certainly help. The idea that not merely the development of alternative energy resources, but the more efficient use of the existing ones must guide us into the future, stands at the centre of the project "The 2000 Watt Society" that was initiated in the Domain of the Swiss Federal Institutes of Technology' in 1998. According to the project, ways and means should be developed to reduce the primary energy demand per capita from its present level of about 6000 W (including the import of grey energy amounting to about 25% of the energy produced within Switzerland) to about 2000 Watt per person, the present global average. Here the target of 2000 W serves as an example of a technically feasible level as much as Switzerland stands for a typical industrialized country with a growing tertiary sector.

As shown in table 6, in 1995 45% of the Swiss end energy utilization was related to the operation of buildings, another 33% to transportation of people and goods. Both sectors bear a tremendous potential for energy savings. Whereas for the transportation sector it is mainly what people consider to belong to a modern life style (private instead of public transportation, big and heavy cars instead of small ones, etc.), the reduction of the energy demand of buildings meets less resistance from the consumers, although it needs much time.

Over the past two centuries, Switzerland has been transformed into a gigantic system of constructed facilities. Currently, some two million buildings are interconnected by a sophisticated network of infrastructure comprising transportation systems (railways, roads, waterways and airports), systems for water distribution, for waste water and solid waste management, for the production and distribution of energy, and for information exchange and telecommunication. The totality of this infrastructure including all public and private buildings ("Constructed Switzerland" – CS) is valued at about 3000 billion Swiss francs (present rebuilding costs). This corresponds to the total output of the Swiss economy of about one decade.

In the coming century, CS is not likely to grow as fast as it has in the past. Rather, the main challenge in the next century will be to efficiently and sustainably manage (i.e., operate, maintain and renew) the vast assets of constructed facilities which have been created in this century. This genuinely new challenge must be met within given spatial, economic and natural resource constraints in a world which faces rapidly changing technological opportunities, social structures and values. Presently, CSs maintenance and renovation costs about 43 billion Swiss francs annually – and this is insufficient to meet sustainability criteria in many cases.

Thus, the task of the coming generations will be very different from the challenges faced by the past generations who built CS. On the one hand, the next generations will inherit a solid infrastructure and a powerful economy. On the other hand, this legacy sets significant constraints on future economic and social development that can only be changed over a period of decades or generations. For example, today the average energy demand per square meter and year is more than three times greater than what can be achieved presently virtually without extra costs. One recipe for the 2000 Watt Society must thus be to lower this value by applying the best available standards when ever new buildings are built and existing ones renovated. Other potential savings are listed in table 6.

The energetic basis of Switzerland as a 2000 Watt Society would be simple and flexible. According to table 4, in 2050 between 900 and 1100 Watt per person could still be produced from fossil fuels. Later, this number would decrease to about 300 W. Another 700 Watt per person would come from already existing hydroelectric power plants, while the rest (200 W increasing to about 1000 W) can easily be provided by new renewable resources (solar, wind, geothermal). Nuclear power would no longer be needed in this picture.

6. Conclusions

We have shown that in a world with fast growing energy demands the present dominant energy strategy of decarbonization is by far too slow to keep the atmospheric carbon emissions at a level which would be in accordance

Table 6
Utilization of end energy per capita in Switzerland by sectors. Values in percent of the average per capita utilization of end energy in 1997 (3600 W p.c.).

	1980	1995	2050	Potential savings in a 2000 Watt Society
Buildings private housing, industry, public sector (incl. lighting and warm water)	47	45	15	Reduction of energy for heating/cooling by a factor 3 relative to the present average standard
Transportation people and goods	25	33	16	Change to energy-efficient modes of transportation. Saturation of demand for mobility
Production agriculture, industry, services	22	22	11	Based on a recent study by the Swiss Academy of Engineering Sciences[a]
Total	94	100	42[b]	

[a] From [11].

[b] Corresponds to a mean per capita utilization of end energy of about 1500 W. According to typical efficiencies of modern energy systems (cogeneration of heat and electricity, heat pumps, etc.) this energy can be produced from not more than 2000 W of primary energy.

with the recommendations of the IPCC. We thus propose that the reduction of the per capita energy demand in industrialized countries to about 2000 Watt per capita within the next 50 years would increase the chances of the new renewable energies to reach a significant contribution to the global energy system. Technically, a country like Switzerland could live easily with 2000 Watt per capita, but the conversion of “Constructed Switzerland” would take several decades. Therefore, it is important to start soon.

Nothing has been said about the economic side of the proposed changes. There are simply no reliable numbers, neither for the conventional nor the visionary energy pathways. The same is true regarding the costs caused by the consequences of climatic changes. Cost estimates are usually based on the assumption of marginal changes. They are linear extrapolations from present cost structures and thus not capable to deal with non-marginal conversions of the energy system (see [6]).

The 20th century has seen two world wars and many smaller conflicts after which large portions of the world had to be rebuilt. Although the capacity for change is limited over a time horizon of 10 years, it is enormous over a period of 50 years. Within the next 50 years, every building will undergo at least one major renovation, and many new buildings will be built while older ones will disappear. If the energy-relevant measures are combined with these activities, extra costs are not prohibitive. Consumer goods are turned over on a much smaller time scale. Cars which use less gasoline are not necessarily more expensive than present cars if the latter are replaced by the former at the usual renewal rate. And the same is true for many other goods.

The main unknown and the biggest risk are people themselves. It is much easier to insulate a building than to change the mobility trends of people. Thus, the fate of the 2000 Watt Society will be determined in the head of people, not at Wall Street. Yet, if we miss the change, agreements like the one of Kyoto will remain dead paper and atmospheric carbon dioxide will continue to grow.

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