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What might be the energy demand and energy mix to reconcile the world's pursuit of welfare and happiness with the necessity to preserve the integrity of the biosphere?

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ABSTRACT

In today's global energy mix with a share of 80% fossil energy, the growth of the world population and energy demand will lead to a conflict between stable ecosystems and global welfare. The inspection of social indexes of welfare and happiness leads to the following energy plan: high-income countries with a current annual energy demand of up to 8 tonnes of oil equivalent per capita (toe pc) have to reduce their demand to 2 toe pc, which should be sufficient without cutback in welfare. Vice versa, low-income countries increase their demand until 2 toe pc are reached. Compared to today this scenario (2 toe pc, 9 billion people by 2050) leads to an increase of the ecological footprint from today 1.3 to 2 planet Earths in today's technologies. The only solution to provide 2 toe pc without damaging the biosphere is a reduction of the CO_2 footprint with a current share of 50%. A complete shift from fossil fuels to renewables would half the ecological footprint as needed for the desired footprint of one planet Earth. To reach this goal, one or more forms of solar power and/or nuclear power are needed, as the potential of non-solar renewables is too small.

1. Introduction

The current status of the world's energy consumption and energy mix, the continuous growth of the world population from 6.8 (October 2009) to about 9 billion by 2050, and today's still growing global energy demand will inevitably lead to a conflict between a happy planet (stable ecosystems, clean environment) and a happy world population (stable societies, global welfare). Thus, the question arises how the world's unceasing demand for energy can be reconciled with the absolute necessity to preserve the integrity of the biosphere.

To analyse the 21st century sustainability threats (at least) four key questions have to be answered in order to deduce guidelines, e.g. for politicians of what has to be done with regard to future energy consumption and energy mix:

1. What is the minimum energy demand per capita to ensure prosperity, welfare and happiness of a society (country, region, etc.). In other words, how much energy is really needed to reach a happy population (stable society, sufficient welfare, etc.)?
2. What is then the possible reduction of the energy consumption per head in currently high-income countries (OECD) without substantial cutback in welfare and happiness, and vice versa the increase of consumption that has to be awarded to underdeveloped or developing countries, as their energy consumption per head is today still low (Tables 1 and 4).
3. What is on the other (even more important) hand the maximum global energy consumption to ensure stable ecosystems, i.e. to ensure a happy planet?
4. Finally, how can we reconcile the world's future energy demand to ensure welfare for all people with the absolute necessity to preserve the integrity of the biosphere?

An attempt to answer these four questions is made in this paper, thereby primarily focussing on energy and not on other main problems like food or water demand or social aspects like literacy or life expectancy although all these aspects are somehow also linked to the energy demand as clearly shown in Tables 1 and 2 for selected countries, but these aspects are beyond the scope of this paper.

At first, the status quo of global energy consumption is inspected in this paper to provide a basis for further discussion. The global demand of energy and today's reserves and resources of fossil fuels are outlined in the following two sections. Thereafter, a typical example of the projected energy demand and mix until 2100 (Section 4) and a short survey on the relationship of energy consumption and world population in the last decades are given (Section 5).

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Table 1
Annual energy consumption in tonnes of oil equivalent (toe) per capita (pc) (1 toe = 41.87 GJ), water footprint and food consumption in selected countries (data for water from Hoekstra and Chapagain (2007) and for food from FAO (2009)).

Country	Annual energy consumption (2007) in toe pc	Water footprint, i.e. daily consumption in m^3 pc (period from 1997–2001)		Daily food consumption (2003) in kcal pc
		Total water[a]	Domestic water	
USA	7.75	6.8	0.60	3753
Russia	4.75	5.1	0.27	3117
Germany	4.03	4.2	0.18	3483
Japan	4.02	3.2	0.37	2767
China	1.48	1.9	0.07	2940
India	0.53	2.9	0.10	2472
World	1.82	3.4	0.16	2808

[a] The water footprint is the extent needed as domestic water (drinking, washing, bathing, etc.) and for the production of agricultural and industrial goods. For the latter two categories, the internal and external footprints have to be considered. The internal footprint is the water needed for the production of goods in the national economy minus the virtual water export to other countries related to the export of domestically produced goods. The external footprint of a country is defined as the water used in other countries to produce goods and services consumed by the inhabitants of the country concerned.

Table 2
Energy consumption and some social indicators of selected countries (CIA, 2009).

Country	Annual energy consumption (2007) in toe pc	Internet user per 1000 persons	Literacy in percent of population with age 15 and over that can write and read	Life expectancy at birth in years
USA	7.75	726	> 99	78
Russia	4.75	214	> 99	66
Germany	4.03	518	> 99	79
Japan	4.02	693	> 99	82
Mexico	1.74	205	91	76
China	1.48	189	91	73
India	0.53	60	61	70
Ethiopia	0.29	3	43	55

To derive answers to the first two questions, four different indicators that describe the situation in a society/country are used, the gross national product per capita (pc), which is a measure of the average prosperity (Section 6), the proportion of undernourished in total population (Section 7), the human development index (HDI), which characterises welfare (Section 8), and finally the subjective well-being index (SWI), which is a measure of the average happiness and life satisfaction in a given society (Section 9).

For an attempt to answer the third question, the ecological footprint as a measure of the demand on the Earth's ecosystems is introduced (Section 10), and finally the respective conclusions with regard to the main question four are drawn in Section 11.

2. Starting point: today's global energy consumption and fuel shares

Today, the annual global primary energy consumption is 12 billion tonnes of oil equivalent (1 toe = 41.87 GJ). The three fossil fuels crude oil, coal and natural gas fill about 80% of this global energy supply (Table 3).

Fossil fuels are relatively concentrated pure energy sources, technically easy to exploit, and at least until today still provide cheap energy. Crude oil products provide almost all of the world's transportation fuels and are the basis of most organic chemicals from bulk to fine chemicals (polymers, pharmaceuticals, dyes, etc.). Coal and natural gas mainly provide heat and electricity and also chemicals like ammonia and hydrogen, and synthetic fuels via Fischer–Tropsch and methanol synthesis. This dominant role of fossil fuels – above all of crude oil – for fuels and chemicals will not change in the near future, but has to change in the next decades as outlined below.

Table 3
Fuel shares of global energy consumption in 2007 (IEA, 2007, 2009; BP, 2009).

Energy type	Share of the world's primary energy consumption
Crude oil	34.0%
Coal	26.5%
Natural gas	20.9%
Nuclear[a]	5.9%
Total fossil fuels and nuclear	87.3%
Hydro[b]	2.2%
Traditional biomass[c]	6.5%
Commercial biomass[c]	3.3%
Other (geothermal, wind, solar, tide)[b,d]	0.7%
Total renewables	12.7%
World energy consumption	12.0 billion toe (tonnes of oil equivalent, 1 toe = 41.9 GJ)

[a] Nuclear refers to the primary heat equivalent of the electricity produced with an average thermal efficiency of 33% (substitution equivalence method), i.e. a virtual primary energy input of 10 TJ (260 toe) per GWh.

[b] Hydro, wind, tide and solar electricity refers to the energy content of the electricity produced in power plants ("direct equivalence method", 86 toe per GWh). For geothermal electricity generation, 10% efficiency is assumed (860 toe per GWh).

[c] Traditional biomass is not traded for money and is difficult to quantify. Here, the estimated ratio of traditional to commercial biomass of two to one is used (based on data for 2003 (IEA, 2007)).

[d] The values for 2004 are 0.41% geothermal, 0.06% wind, 0.04% solar and 0.0004% tide (IEA, 2007).

The contribution of nuclear and hydropower – which are only used to produce electricity – to the global primary energy consumption is about 6% and 2%, respectively. The share of biomass on the global energy supply is about 10%. The majority – about two-thirds – is traditional biomass, which is not traded for

Table 4
Regional distribution of consumption of primary energy 2007 (IEA, 2007, 2009).

Region	Consumption in Gtoe (2007)	Share of renewables in total energy in percent (2004)		
		Combustible renewables, waste (%)	Hydro (%)	Geothermal, solar, wind (%)
OECD	5.50	3.0	2.0	0.7
China	1.97	13.5	1.9	–
Asia[a]	1.38	29.4	1.3	1.1
Former USSR	1.02	0.8	2.1	0.04
Non-OECD Europe	0.11	5.8	4.6	0.3
Africa	0.63	47.6	1.3	0.2
Latin America	0.55	18.0	10.4	0.4
Middle East	0.55	0.2	0.3	0.2
World	12.03[b]	10.6	2.2	0.4

[a] Excluding China.
[b] Including international aviation and marine bunkers as well as electricity and heat trade (0.32 Gtoe).

money and difficult to quantify, and that has the severe problem of a currently still negligible reforestation. Other renewable energy sources such as geothermal, solar, wind and tide energy currently do not play a remarkable role on a global basis (0.7%), but the application is increasing and supported by some countries, which now have achieved relatively high levels of wind power penetration, such as 19% of electricity production in Denmark, 11% in Spain and Portugal, and 7% in Germany in 2008.

The regional distribution of primary energy consumption as well as the share of renewables differ considerably (Table 4). For example in Africa, 48% is covered by traditional biomass.

At present a relatively small part of the world's population has the lion's share of the global energy consumption (Table 5). The OECD countries with a population of 1.2 billion people, which equates to 18% of the world's population, have a share of 47% of the global energy consumption and consume thrice as much as China although the population is similar. In Asia (excluding China) and Africa, the energy consumption per capita (pc) and year is only 0.7 toe (tonnes of oil equivalent) compared to the OECD-value of 4.6 toe pc and year. (For readers who are not used to the unit "toe": 1 toe per year is equivalent to 1330 W.)

Table 5
Regional distribution of population and of specific energy need 2007 (IEA, 2009).

Region	Population in billion	Energy consumption in toe per capita and year	Share of global energy consumption (%)
OECD	1.19	4.64	47.0
China	1.33	1.48	16.8
Asia (excluding China)	2.15	0.64	11.8
Former USSR and non-OECD Europe	0.34	3.34	9.7
Africa	0.96	0.66	5.4
Latin America	0.46	1.19	4.7
Middle East	0.19	2.86	4.6
World	6.62	1.82	100

3. Current reserves and resources of fossil fuels

It is generally accepted that fossil energy resources are limited, although it is a matter of debate how much is left. For the discussion on the availability of fuels, the following definitions are helpful: Reserves are currently technologically and economically recoverable, whereas resources are the additionally demonstrated quantities that cannot be recovered at current prices with current technologies but might be recoverable in future.

Beside conventional gas, oil and coal resources, we also have to consider non-conventional resources (Table 6). Oil sands, extra heavy oils and oil shale are estimated to contain three times as much oil as the remaining conventional oil reserves. But – with the exception of Canadian oil sands – they are not yet economically recoverable but this may change.

About 50% of the conventional natural gas reserves are located in countries far away from consumers, for example in the Middle East. In these regions where moving gas by pipelines is not possible or not economical, it can be transported as liquefied natural gas (LNG) by cryogenic sea vessels. The continued cost reduction of LNG transport during the last two decades has lead to a strong increase of LNG production from 50 million toe (4% of global gas demand) in 1990 to 147 million (7%) in 2006. As an alternative to LNG transport, Fischer–Tropsch (FT)-plants were built in Qatar, Malaysia and South Africa to enable exploitation of stranded gas by conversion to liquid fuels (mainly diesel oil). The current capacity of gas based FT-plants is 5 million toe, and it is expected that this will grow to 30 million in the next decade. Even then this would only substitute 1% of the current oil demand.

Table 6
Reserves and resources of fossil fuels 2004/2006 (BGR, 2004; Kuempel and Rempel, 2008).

Fuel type	Reserves[a] in billion toe	Resources[a] in billion toe
Crude oil	163	82
Natural gas	161	184
Total conventional hydrocarbons[b]	324	266
Oil sands and extra heavy oil	66	66
Oil shale	1	184
Non-conventional natural gas[c]	1	1538
Total non-conventional hydrocarbons[d]	68	1788
Hard coal	440	2248
Soft brown coal	46	209
Total coal	486	2457
Fossil fuels total	About 900	About 4500

[a] For definitions see text at the beginning of this section.
[b] Data for 2006 (Kuempel and Rempel, 2008).
[c] Tight gas (6%), coal-bed gas (9%), aquifer gas (52%) and gas hydrates (33%).
[d] Data for 2004 (BGR, 2004).

There are also large unconventional gas resources, like methane hydrate or aquifer gas, that could increase the amount of gas resources by a factor of about ten. Methane hydrate is a clathrate in which methane molecules are trapped. Hydrates are stable at high pressure and low temperatures (e.g. $<13\,^{\circ}C$ at 100 bar), and are found at an ocean depth of more than 500 m as well as under permafrost conditions. Some experts argue that the quantities of methane hydrates exceed those of all other fossil fuels combined, but it must be noted that all content estimates of methane hydrates are highly speculative at the present time (Esteban, 2003). In addition, hydrates mostly occur in disseminated grains with most pure hydrates in a thickness range of 1–100 mm (e.g. Torres et al., 2008). Technologies for extracting methane from hydrate deposits have not yet been developed, and it may be impractical to mine these with a positive return on energy. It should also be noted that CH4 – if e.g. accidently released to the atmosphere – has 20 times more impact per unit weight than CO_2 with regard to the contribution to global warming.

Compared to oil and gas, the coal reserves and above all the resources are huge (Table 6) and may be increasingly used during oil and gas depletion, e.g. by India, China and Australia. But this will increase the CO_2 emissions, at least without the recently discussed storage of CO_2 in geological formations such as former oil or gas wells. The specific CO_2-emissions are 4 tonnes CO_2 per toe for coal compared to 3.3 and 2.4 for oil and gas, e.g. switching from a gas fired power plant to a coal fired plant increases the emissions by 70%.

Table 7 shows the reserves-to-production ratios, indicating that the current reserves will last for about 60 years for oil and gas and 170 years for coal. These numbers are static values based on current prices, technology and energy demand. If for example a constant growth rate of crude oil consumption of 4% is assumed, the reserves-to-production ratio for crude oil, oil sands and oil shale would be only about 30 years (compared to the static value of 60 years as given in Table 7). Thus, the static numbers may lead to unrealistic expectations of the future availability of fossil fuels. For example, the ratios will increase, if the energy price increases, and decrease, if global demand increases. The status of world oil (and other fossil fuel) reserves is a contentious issue, polarised between advocates of peak oil who believe production will soon decline, and oil companies that say there is enough oil to last for decades. While there are certainly vast amounts of fossil fuel resources left in the ground (see Table 5), the volume of oil that can be commercially exploited at prices the global economy has become accustomed to is limited and will soon decline. The result is that oil may soon shift from a demand-led market to a supply constrained market (Owen et al., 2010). The capacity to meet the services provided by future liquid fuel demand is contingent upon the rapid and immediate diversification of the liquid fuel mix, the transition to alternative energy carriers where appropriate, and demand side measures such as behavioural change and adaptation. The successful transition to a poly-fuel economy will also be judged on the adequate mitigation of environmental and social costs (Owen et al., 2010).

Notwithstanding these aspects, the following estimation may be helpful to get at least a rough estimation of the availability of fossil energy: By about 2050, the world population will be about 9 billion compared to about 7 billion today. Assuming an average population of 8 billion and an energy demand of 2 toe per capita and year, we would then have an annual global energy demand of 16 billion toe. If this demand is completely covered by fossil fuels, this would last for 100 years, if all the reserves and only 16% of the resources are used. Thus, the availability of fossil energy is – at least for the next 100 years – not the problem that is of primary concern. The major problem lies in the effects caused by the CO_2 produced when fossil fuels are burned (see Section 10).

In the long run, fossil fuels are finite and should be used with care for the generations to come. Just imagine, we would not use the majority of crude oil (about 90%) for the production of fuels like gasoline, jet fuel, diesel and heating oil but now only for chemicals. This would increase the reserves-to-production ratio by a factor of about 10, i.e. crude oil would then last for several hundred years! But such a desirable decoupling of feedstock and energy cannot be expected in the near future, and the chemical industry will remain the free-rider of energy consumption.

The regional distribution of the reserves and resources of fossil fuels is listed in Table 8. More than 40% of the current reserves of gas and crude oil are located in the Middle East whereas the

Table 7
Reserves and resources of fossil fuels in 2004 (BGR, 2004).

Fuel type	Consumption in billion toe per year	Reserves in billion toe	Resources in billion toe	Reserves-to-production ratio in years	Resources-to-production ratio in years
Crude oil, oil sands, oil shale	3.8	230	332	60	87
Conventional and non-conventional natural gas	2.3	141	1639	61	713
Coal	2.8	486	2457	174	878

Table 8
Regional distribution of reserves and resources of fossil fuels in 2004 (BGR, 2004).

Region	Crude oil, oil sands, oil shale		Natural gas		Coal	
	Share of reserves	Share of resources	Share of reserves	Share of resources[a]	Share of reserves	Share of resources
Europe	1.5%	1.7%	3.4%	5.3%	5.6%	5.5%
Former USSR	11.6%	15.4%	31.8%	23.2%	19.0%	35.2%
Africa	7.2%	4.8%	7.7%	7.9%	5.8%	0.2%
Middle East	48.2%	9.8%	40.0%	11.9%	0%	0.4%
Asia, Australia	4.0%	8.8%	8.1%	22.2%	39.3%	47.7%
North America	16.5%	43.8%	5.2%	17.1%	28.0%	10.7%
Latin America	11.0%	15.7%	3.8%	12.4%	2.3%	0.3%
World (10^9 toe)	230	332	141	1639	486	2457

[a] Without gas hydrates.

majority of the coal reserves are located in North America, Australia and Asia. This highly non-uniform distribution of the reserves as well as of the resources of fossil fuels (primarily of crude oil) will play an important role in future (struggle for resources, etc.) and is a political risk, above all for Europe, where the reserves and resources are rather limited.

4. Projected energy demand and energy mix of the future

The energy demand is rising world-wide, especially in booming countries like India and China. The future will show whether nuclear power will be abandoned in some countries or its share will increase as currently only nuclear power and to a smaller extent hydroelectricity are significant alternatives to fossil fuels, but this may change (as discussed in Section 11).

In the past, there have been alarming predictions by groups such as the Club of Rome that the production peak of oil world would be reached in the late 20th century. This was not exactly the case, but according to a recent study of Aleklett et al. (2010), the global oil production has very probably now passed its maximum, which implies that we have reached the peak of the oil age. Anyway, in the long run the world will struggle to provide (cheap) oil, and costly and less productive methods such as deep sea drilling will have to be used. As discussed by Schollnberger (2006), the global pattern of primary energy consumption will change profoundly during the 21st century, which will create a new energy mix (Fig. 1).

The global demand might grow from today's value of 12 billion toe to 35 billion in 2100, and renewables (hydro, wind, biomass, solar, geothermal) may then fill 35% (Fig. 1). The share of nuclear power is expected to be 20%. Fossil fuels will still be important but with a smaller share of about 30% in 2100. The rest of 15% is covered by other sources (waste, oil shale, currently unknown technologies).

One (out of many published scenarios) of the evolution of renewables until 2030 is shown in Table 9. According to the International Energy Agency, the share of renewables in global energy consumption will remain unchanged in the next 20 years at around 14%. The share of traditional biomass (currently 7% of the world's energy demand) will fall to about 2% as developing countries shift to modern forms of energy, but this will be compensated as renewable energy will play an increasing role in the field of electricity generation, as transportation fuel and for heating purposes (Table 9).

According to the forecast depicted in Fig. 1, energy generation using renewable energy is expected to become significant within the next 100 years. Competition between different fuels will be strong in the second half of the 21st century. The anticipated energy mix for 2100 as shown in Fig. 1, which is also predicted in a similar way by most other published scenarios, could give future generations a chance to obtain the energy needed to prosper. But if only the share and not the absolute level of fossil fuel consumption is reduced, the CO_2 emissions would be almost the same (or even higher if the share of coal increases within the share of fossil fuels, see Fig. 1), which would lead to an increase in global warming. Thus, if some previously unheard technology will

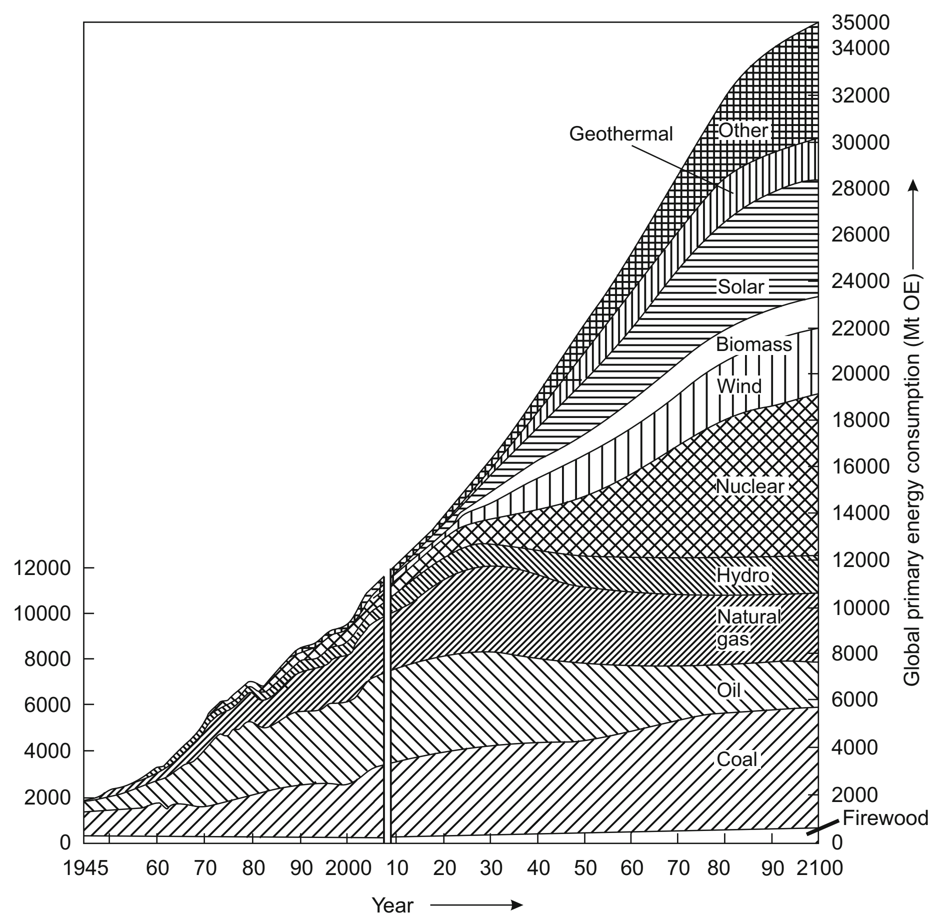

Fig. 1. Global primary energy mix: history and outlook as projected by Schollnberger (2006). The figure is based on weighting the component "sustained strong economic growth" with 0.5, the component "security of energy supply" with 0.3 and "ecological precaution" with 0.2 throughout the 21st century; others: oil shale, hydrogen, waste incineration; electricity from nuclear, hydro, etc. is counted by using the substitution equivalence method.

not develop during this century, the only chance is a drastic decrease of the current growth rate of the global energy consumption so that the predictions shown in Fig. 1 (still too much energy demand and share of fossil energy) and in Table 9 (still insufficient share of renewables) will not come true.

5. World energy consumption and world population

One of the major driving forces of the world's energy demand is the growing world population. Today (2009), the world population grows by 1.2% per year, which is equivalent to the current population of Germany (around 80 million). (If you read this paper carefully within about 20 min, the global population will have grown by about 3000 people.) In the hypothetic case of an undamped demographic evolution the world population would double in 60 years. This growth will certainly lead – at least in the near future – to a further rise of the global energy consumption. Thus, it is instructive to have a look at the history of the world's energy consumption and population as shown in Fig. 2 for the period from 1965 to 2008.

The growth of the world population and of the global average welfare have led to an increase of the energy consumption from 3.8 billion toe in 1965 to 11.3 billion toe in 2008

Table 9
Projected global increase of renewable energy until 2030 (IEA, 2007, 2006).

Energy field	2004		2030[a]	
Electricity	Electricity generation in TWh	Share of total electricity generation (%)	Electricity generation in TWh	Share of total electricity generation (%)
Hydropower	2810	16.4	4903	18.7
Biomass	227	1.0	983	3.8
Wind	82	0.5	1440	5.5
Solar	4	< 0.1	238	0.9
Geothermal	56	0.3	185	0.7
Tide and wave	< 1	< 0.1	25	0.1
Total renewable used for electricity	**3179**	**18.2**	**7775**	**29.7**
Biofuels	Biofuels in Mtoe	Share of biofuels used for fuels	Biofuels in Mtoe	Share of biofuels used for fuels
	15	**1.0**	**147**	**4.6**
Industry and Buildings	Renewables in Mtoe	Share of renewables for industries and buildings	Renewables in Mtoe	Share of renewables for industries and buildings
Commercial biomass	261	5.2	450	5.9
Solar heat	7	0.1	64	0.9
Geothermal heat	4	0.1	25	0.3
Total renewable for industries and builings	**272**[b]	**5.4%**[b]	**539**[b]	**7.1**[b]
Global primary energy consumption	Renewables in Mtoe	Share of renewables for total primary energy consumption	Renewables in Mtoe	Share of renewables for total primary energy consumption
	11.1	**13**[c]	**16.5**[a]	**14**[c]

[a] Assumption of an increase of primary and final energy consumption in 2030 (compared to 2004) by 50%.
[b] Without traditional biomass.
[c] Including traditional biomass (7% in 2004 and 2% in 2030 of total primary energy).

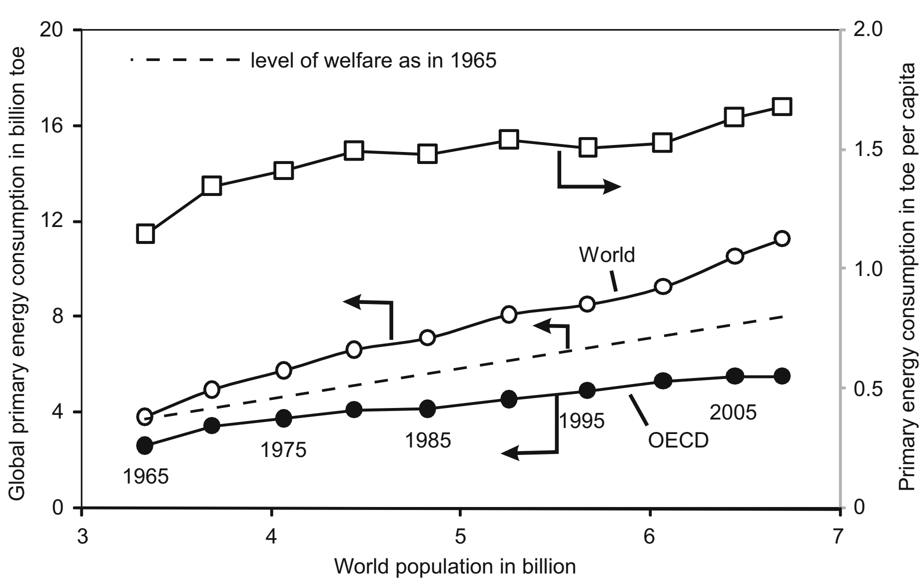

Fig. 2. Relationship of world primary energy consumption (without traditional biomass) and world population in the period 1965–2008 (1965, 1970…2005, 2008).

(traditional biomass not counted). The energy consumption has tripled during this period whereas the world population has "only" doubled. Thus, without industrialisation and increase in welfare in today's high-income and some developing countries the demand would have "only" grown to 7.6 billion toe (dashed line in Fig. 2). In other words, the growth of the global energy consumption during the last four decades can be attributed in equal portions to the growth of welfare and of population. This more than proportional increase of the energy demand with the growing world population is also reflected by the history of the average global energy consumption per head, which has increased from 1.2 toe pc in 1965 to 1.7 toe pc in 2008 (Fig. 2). At least in the near future, this trend will probably persist and will be driven by strongly developing countries like India and China where only during the past ten years the energy demand per head has increased by 105% and 36%, respectively.

6. Energy consumption and gross national product

Usually, the gross national product (GNP) (or the gross domestic product (GDP), see footnote b of Table 10) is used as a measure of a country's economic performance. For a fair comparison of countries, the purchasing power parity (PPP) should be taken, i.e. the GNP in international dollars with the same purchasing power as a US $ in the USA. The respective values in important countries are given in Table 10. In addition, the land area per head, the current population (and the prediction for 2050), and the energy consumption (pc) are listed.

The current mean global land area per head is only two soccer fields, which include areas that can be used only to a small extent (Antarctica, deserts, etc.). In future, not only energy but also the available land area will be a limiting factor to provide the world with energy, water and food, e.g. in countries with currently already less than one soccer field per head.

Fig. 3 shows the relationship of the gross national product (GNP) per capita (pc) and the primary energy consumption (pc). Up to a GNP of about 15,000 US $ pc, an increase of the GNP is associated with an almost proportional increase of the energy consumption. For higher values of GNP pc, the development in certain high-income countries (Europe, Japan) gives rise to a certain optimism, which reflects the positive effect of efficient energy systems. Obviously, the doubling of the GNP pc from 15,000 to 30,000 US $ is also possible with a disproportional increase of the energy consumption of "only" 50%, as indicated by the dashed-and-dotted line in Fig. 3 (increase of energy consumption from 2.1 to 3.2 toe pc.) Nevertheless, more technical improvements are still needed in combination with restrictions of the individual energy consumption in certain currently rich nations (e.g. in the USA). With regard to the global energy consumption also fast developing countries like China and India should improve the efficiency of their energy systems (traffic, electricity, etc.) to avoid a further strongly proportional increase of the energy consumption per capita with increase in GNP.

7. Energy consumption proportion of undernourished in total population

A first indicator of what the minimum energy demand needed per capita (at the current standard of technology) might be is the proportion of undernourished in the total population. The correlation of the proportion of undernourished and the primary energy consumption per capita of selected underdeveloped and developing countries is shown in Fig. 4.

For all countries with an annual energy consumption of more than 2 toe pc (e.g. OECD countries), the proportion of undernourishment is negligible and therefore not shown. According to Fig. 4, a minimum energy demand in the range of 1.5–2 toe per capita and year is needed at the current status of technology to guarantee that starvation can be excluded, at least if the differences in income and welfare equality in a country are not too large.

8. Energy consumption and status of human development

Countries with a higher (average) gross national product per head may be more likely to also score highly on other measures of

Table 10
Population (2009 and estimates for 2050), energy demand, land area and gross national product of selected countries (IEA, 2009, World bank, 2009, US Census Bureau, 2009).

Rank by Population in 2009	Country	Population in million 2009 (in 2050[a])	Annual energy consumption in toe per capita	Annual GNP PPP[b] in 2008 $ per capita	Land area in soccer fields[c] per head (2009)
1	China	1339 (1424)	1.48	6020	0.7
2	India	1166 (1656)	0.53	2960	0.3
3	United States	307 (439)	7.75	46,970	3.0
4	Indonesia	240 (313)	0.84	3830	0.8
5	Brazil	199 (261)	1.23	10,070	4.2
6	Pakistan	176 (276)	0.51	2700	0.4
7	Bangladesh	156 (234)	0.16	1440	0.1
8	Nigeria	149 (264)	0.72	1940	0.6
9	Russia	140 (109)	4.75	15,630	12.1
10	Japan	127 (94)	4.02	35,220	0.3
11	Mexico	111 (148)	1.74	14,270	1.7
14	Germany	82 (74)	4.03	35,940	0.4
15	Ethiopia	85 (278)	0.29	870	1.3
53	Australia	21 (29)	5.87	34,040	36.3
	World	6790 (9320)	1.82	7448	2.2

[a] Estimations of US Census Bureau (2009).
[b] The gross national product (GNP) is a basic measure of a country's economic performance and comprises the total value produced within a country (i.e. its gross domestic product GDP) together with its income received from other countries less similar payments made to other countries. PPP is purchasing power parity; an international $ has the same purchasing power as a US $ in the United States.
[c] Assumption: the typical area of a soccer field is 10,000 m^2 (=1 ha).

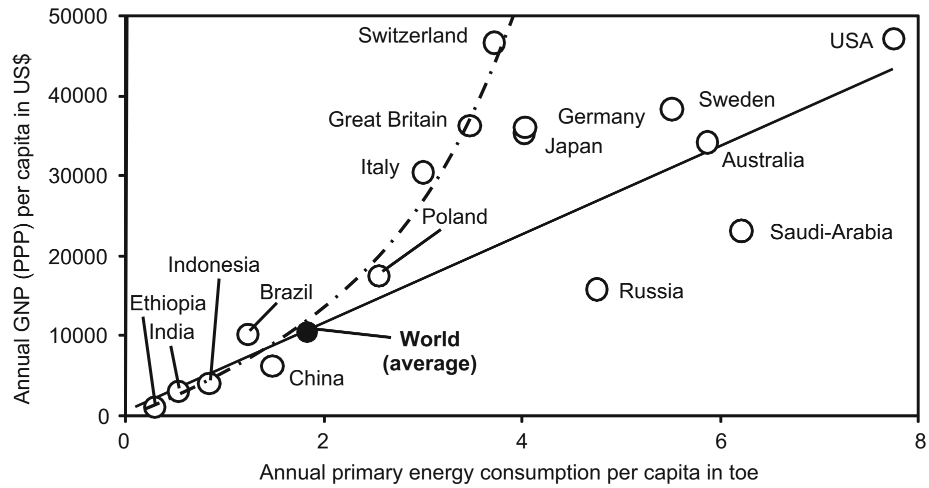

Fig. 3. Gross national product in purchasing power parity per capita (2008) versus primary energy consumption pc (2007) (solid line with slope of current global average; dot and dash line indicates the development in countries with increased energy efficiency).

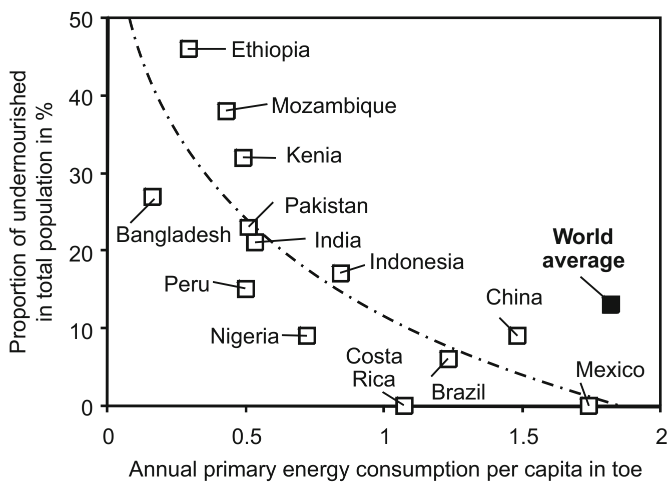

Fig. 4. Proportion of undernourished in total population (2003–2005) (FAO, 2008) versus primary energy consumption pc (2005). Note that for all countries with an annual energy consumption of more than about 1.5 toe pc the proportion of undernourishment is negligible.

welfare, such as life expectancy. However, there are serious limitations to the usefulness of GNP as a measure of welfare:

- Measures of the GNP exclude unpaid economic activity like domestic work such as childcare.
- The GNP does take into account the inputs used to produce outputs, e.g. the working time needed to create a certain GDP (happiness of workers, leisure time).
- The impact of economic activity on the environment is not measured by the GNP.
- The GNP does not measure the quality of life, such as the quality of the environment, the security from crime and health care, and the population health and longevity.
- The GNP only reflects the average wealth, i.e. a country may have a high average per-capita GDP but the majority of its citizens have a low level of income due to concentration of wealth in the hands of a small fraction of the population. Such differences in income equality are measured by the Gini coefficient, which is a number between 0 and 1, where 0 corresponds to perfect equality – everyone has the same income – and 1 corresponds to perfect inequality (one person has all the income, and everyone else has no income). In Japan and Central and Northern Europe, the inequality is low (e.g. in Denmark, Japan and Schweden with Gini$<$0.25), whereas in many countries in Africa and South America the inequality is very high (e.g. in Brazil, Bolivia, Botswana, Colombia, Haiti and Namibia where Gini$>$0.55), while the United States are midfielders (Gini=0.41) (United Nations Development Programme, 2007).

Since 1990, the Human Development Index (HDI) is published as an index to characterise the level of human development with regard to life expectancy, education and purchasing power (United Nations Development Programme, 2007). The HDI is used to rank countries by level of "human development", and combines normalized measures of life expectancy, literacy, educational attainment and GDP per capita. To transform a raw variable x into a unit-free index between 0 and 1 (which allows different indices to be added together), the following formula is used:

$$\text{(unit free, i.e. normalised) } x\text{–}index = \frac{x - x_{min}}{x_{max} - x_{min}} \quad (1)$$

where x_{min} and x_{max} are the lowest and highest values the variable x can attain.

The HDI combines three basic dimensions and the corresponding indices:

1. The life expectancy index is an index of population health and longevity:

$$Life\ Expectancy\ Index\ (LEI) = \frac{LE - LE_{min}}{LE_{max} - LE_{min}} = \frac{LE - 25}{85 - 25} \text{(with } LE \text{ in years)} \quad (2)$$

2. The education index is measured by the adult literacy rate (with two-thirds weighting) and the gross enrolment ratio (with one-third weighting):

$$Education\ Index\ (EI) = \frac{2}{3}ALI + \frac{1}{3}GEI \quad (3)$$

with

$$Adult\ Literacy\ index\ (ALI) = \frac{ALR - 0}{100 - 0} \text{(with } ALR \text{ as adult literacy rate in \%)}, \quad (4)$$

$$Gross\ enrolment\ index\ (GEI) = \frac{CGER - 0}{100 - 0} \quad (5)$$

The combined gross enrolment ratio CGER (in %) incorporates different levels of education from kindergarten to postgraduate education.

3. The standard of living is measured by the natural logarithm of gross domestic product per capita at purchasing power parity (reason for log-scale is given below):

$$\textit{Gross domestic product (GDP)} = \frac{\log(GDPpc) - \log(100)}{\log(40{,}000) - \log(100)}(\text{pc} = \text{per capita}) \quad (6)$$

This finally leads to the equation to calculate the human development index:

$$HDI = \frac{1}{3}LEI + \frac{1}{3}GEI + \frac{1}{3}GDP \quad (7)$$

Fig. 5 shows the human development index (HDI) versus the gross national product in purchasing power parity per capita. Obviously, the average welfare of a nation as measured by the HDI strongly increases as one moves from subsistence-level poverty to a modest level of economic security and then levels off at about $15,000 per head. Among high-income societies, a further increase in income is only weakly linked with higher levels of HDI, i.e. further gains in income bring relatively little or no change in welfare. For underdeveloped and developing countries, however, there is a clear impact of income on welfare.

As one may expect, not only the GNP pc (Fig. 3) but also the HDI is strongly linked to the energy consumption pc, but again only up to a certain extent, i.e. in poor countries. This is depicted by the plot of the HDI versus the annual energy consumption per capita (Fig. 6).

In underdeveloped ($HDI < 0.5$) and developing countries ($0.5 < HDI < 0.8$), there is a clear relation between the standard of living and the energy consumption, but for developed countries ($HDI > 0.8$), the HDI almost gets independent of the specific energy consumption. Thus, Fig. 6 reflects a well-known law of economics, the so-called diminishing marginal utility, which states that as a person increases consumption of a certain product (here of energy) there is a decline in the utility (here increase of HDI) that a person derives from consuming additional units of that product.

Some other important facts and conclusions can be derived from Fig. 6:

1. Obviously, a minimum energy consumption of at least about 2 toe per capita (pc) is needed at the current status of technology to reach the average HDI value (about 0.95) of high-income OECD countries (Central & Northern Europe, USA, Japan, etc.). Thus, this value can be regarded as the current minimum demand to reach a high status of development.

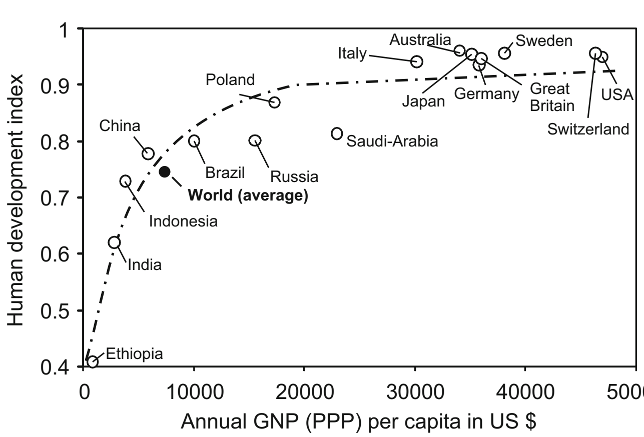

Fig. 5. Human development index (HDI) in 2007 versus gross national product (GNP) in purchasing power parity (PPP) per capita in 2008.

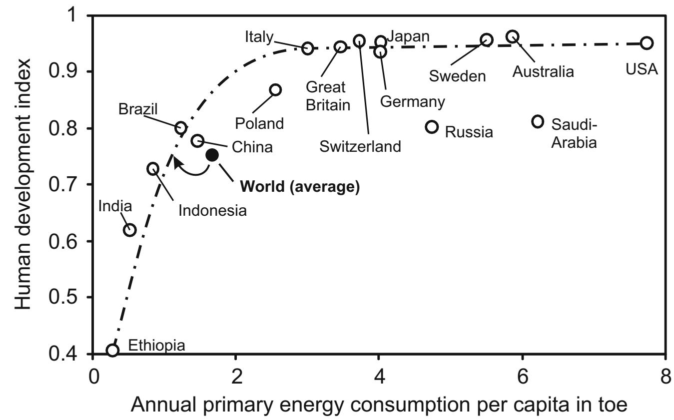

Fig. 6. Human Development Index versus energy consumption per capita. The HDI ranks countries by level of "human development" (HDI) for 2007 from (United Nations Development Programme, 2007). The arrow indicates the theoretical decrease of the global energy consumption per head to the minimum value that we could have today (2008) according to the trend (dot and dash curve) without change of global average HDI.

Remarkably (and by pure chance), this is almost the same value as what is actually the global average (1.8 toe pc and year, Table 9).

2. High income OECD countries (Central & Northern Europe, USA, Japan, etc.) have in principle the chance to reduce their energy consumption to 2 toe pc without (or at least without strong) loss of welfare, whereas underdeveloped and developing countries like India and China inevitably need more energy to increase their current welfare until about 2 toe pc is reached. (Remarks: It is not discussed in this paper that favorable climatic conditions have an influence on the energy demand, e.g. Italy versus Sweden with regard to heating energy. The same is true for densely populated regions compared to less dense populated regions with regard to energy for transport, e.g. Germany and Japan compared to Australia and the Unites States. Thus, the value of 2 toe pc should not been taken for granted, but is a first good indicator).
3. Today, the global (average) HDI value is only 0.75 compared to 0.95 in high-income countries. In principle, this corresponds to a minimum global energy consumption of 1 toe pc and year as indicated by the arrow in Fig. 6 compared to the currently 1.8 toe. In other words, the global energy consumption could be reduced by 40% (from 1.8 to 1 toe pc) without changing today's global mean status of human development.
4. According to UN estimates, the world population will be 9.2 billion in 2050 compared to 6.8 billion in 2009. (Population estimates for the world could ignore significant population shifts as climate change may alter the habitable areas of the globe, but this is not considered here.) Thus, if nothing changes – constant HDI and constant energy consumption per head in all countries – 35% more primary energy will be needed. This would almost completely eat up the potential savings that we could reach at most (see 3).
5. Vice versa, if the global average status of development (hopefully) increases in future, this will inevitably lead to an increase of the energy consumption if we do not change our attitudes of energy consumption.
6. The following scenario for 2050 is instructive. Let us be very optimistic and assume that the current HDI value of high-income OECD countries ($HDI = 0.95$) is then reached globally. Let us further assume that by means of advanced and new technologies and by energy savings – first of all needed to reduce today's energy consumption of high-income

countries – only 2 toe per head and year is consumed in 2050 on a global average. Thus, with a world population of 9.2 billion in 2050, the world would then still need 18.4 billion toe, which is 50% more of what is already consumed today!

Of course, there are other important factors that have to be considered with regard to the conflict between highly developed countries and less developed countries. For example, highly developed countries contribute towards happiness in less developed countries (e.g. communication technology, medicine). Also, highly developed countries export some of their sustainability since they are reliant on primary sector produce from less developed countries without which their happiness will decrease. But it is beyond the scope of this paper to discuss all these aspects in more detail.

9. Energy consumption and human happiness

Some economists argue that although average richer nations tend to be happier than poorer nations, beyond an average GDP pc of $ 15,000 (PPP) per year the average income of a nation makes little difference to the average happiness of a nation (Layard, 2003; Ruckriegel, 2007; Inglehart et al., 2008). Although the HDI already includes elements reflecting the average happiness of a nation, it is still a matter of debate how to measure well-being even better and how to give politicians better guidelines, hopefully not only to win elections. For example, the French President Sarkozy appointed a commission in 2008 to come up with a better measure, chaired by two Nobel laureates, Amartya Sen and Joseph Stiglitz.

Happiness is not easy to define and philosophers, economists, theologians, sociologists and politicians have debated on this term since ancient times. In many societies, the interest in happiness was brought to widespread attention with the moral philosophy that the purpose of politics should be to bring the greatest happiness to the greatest number of people. For example, in 1776 the American Declaration of Independence argued for "certain inalienable rights, that among these are life, liberty and the pursuit of happiness". As such, nations have been formed on the basis of the search for happiness, and this desire has been put on a par with the right to life and the right to freedom. The measurement and analysis of notions such as happiness, welfare, subjective well-being and life satisfaction have a half century history in the social sciences (Easterlin, 2001). In the USA, the General Social Survey (National Opinion Research Center, 2009) has asked the following question since the early 1970s to measure happiness. "Taken all together, how would you say things are these days – would you say you are very happy, pretty happy or not too happy". Table 11 shows the results in the period from 1976 to 2006.

The distribution of happiness is practically unchanged over the period (1976–2006) although the GNP (PPP) per capita has about doubled in the United States and the value of the HDI increased from 0.87 to 0.96 in that period. This finding is surprising since at any time within any community there is a clear relation between happiness and income (Table 12).

It is interesting to note that happiness is directly proportional to log income rather than to absolute income, which is the reason why log GDP is used in Eq. (6).

Instead of happiness the respondents of surveys may be asked about their satisfaction with life as a whole. The happiness and the life satisfaction of a society are measured and combined by the subjective well-being index (SWB) that is in recent years more and more used by economics. Typically the value of the SWB is determined as follows:

Life satisfaction is assessed by asking respondents how satisfied they are with their life, using a scale from 1 (not at all satisfied) to 10 (very satisfied). Happiness is determined by asking how happy respondents are. For a composite measure of the subjective well-being index, the responses to both questions are combined equal weight. Because life satisfaction is measured on a 10-point scale and happiness (according to the data published by Inglehart et al., 2008) is measured on a 4-point scale ("very happy"=1, "rather happy"=2, "not very happy"=3, "not at all happy"=4), and because the two questions have opposite polarity, the SWB is calculated as follows: SWB=life satisfaction $-2.5\times$ happiness. Thus, if 100% of people are very happy and extremely satisfied, a country gets the maximum score of 7.5. If more people are dissatisfied or unhappy than satisfied or happy,

Table 11
Distribution of happiness in the USA in the period from 1976 to 2006 (National Opinion Research Center, 2009).

Average happiness	1976	1986	1996	2006	Total (1972–2006)
Very happy (%)	35	33	32	32	34
Pretty happy (%)	53	57	57	56	55
Not too happy (%)	12	10	11	12	11
Number of informants	1499	1459	2887	2990	45,623
Annual GNP PPP (2006) in 1000 $	23.2	28.9	34.5	45.5	
HDI	0.87	0.90	0.93	0.96	

Table 12
Distribution of US population by happiness at various levels of income in 1994 (Easterlin, 2001).

Total household income (1994 dollars)	Mean happiness rating[a]	Very happy (%)	Pretty happy (%)	Not too happy (%)	Number of cases
75,000 and over	2.8	44	50	6	268
50–74,999	2.6	36	58	7	409
40–49,999	2.4	31	59	10	308
30–39,999	2.5	31	61	8	376
20–29,999	2.3	27	61	12	456
10–19,999	2.1	21	64	15	470
Less than 10,000	1.8	15	62	23	340
All income groups	2.4	28	60	12	2627

[a] Based on score of "very happy"=4, "pretty happy"=2 and "not too happy"=0.

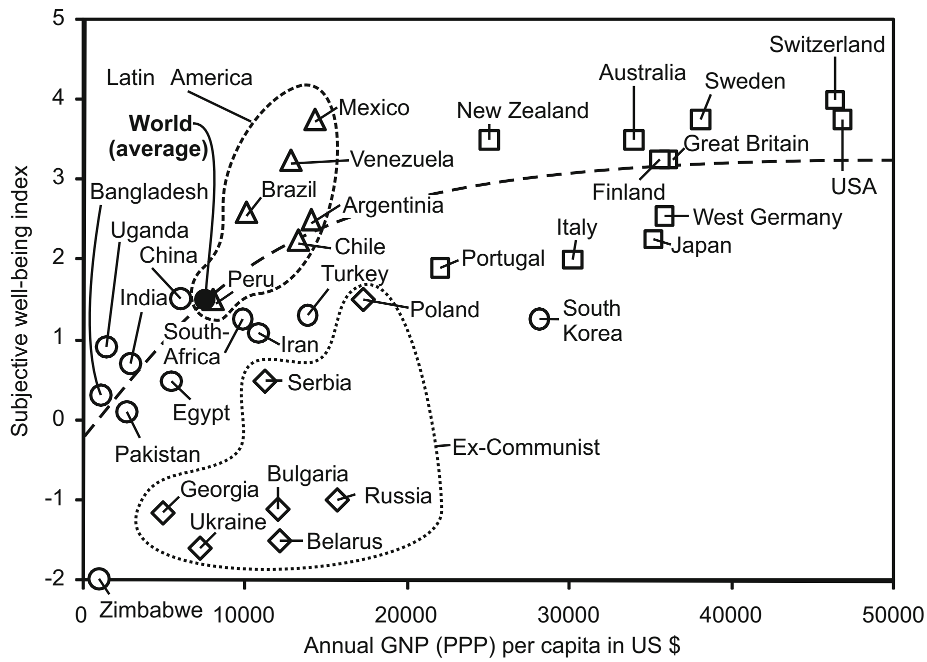

Fig. 7. Subjective well-being index in the period 1995–2007 versus gross national product in purchasing power parity per capita (2008) (SWB from Inglehart et al., 2008; global average value based on 33 countries representing 68% of the world's population).

the country would even get a negative score. Just imagine a country with an extremely inequality – 5% very happy and a score of 10 for satisfaction, 95% not at all happy and score 1 for satisfaction – this would lead to a value of SWB of $-8.2(=0.05\times10+0.95\times1-2.5\times(0.05\times1+0.95\times4))$.

It is far beyond the scope of this paper to discuss philosophical aspects of happiness and welfare in general. But it should be mentioned that a limited degree of unhappiness, lack of welfare and income inequality are certainly needed to create a psychological strain to motivate people, especially young people to do it better as their parents and others did. So each society should ensure the inalienable right of pursuit of happiness but not guarantee happiness.

Fig. 7 shows the relationship between the SWB and the economic development (GNP in PPP per capita) in 33 countries containing 68% of the world's population. The curve (dashed line) depicts the trend. If the SWB of a society is only determined by its level of human development, it would fall on this curve. This curve is therefore similar to the relationship of the human development index (HDI) and the GNP (PPP) per capita (Fig. 5).

Fig. 7 indicates that the SWB of nations is closely related to economic development. People in high-income countries are obviously much happier and more satisfied with life than people in low-income countries, and the differences are substantial. In Denmark, 52% of the public indicated that they were highly satisfied with their lives (placing themselves at about 9 on the 10-point scale) and 45% said they were very happy. In Zimbabwe, only about 5% were highly satisfied with their lives as well as very happy.

Happiness and life satisfaction rise steeply as one moves from subsistence-level poverty to a modest level of economic security and then levels off. Among the richest societies, further increases in income are only weakly linked with higher levels of SWB, i.e. further gains in income bring relatively little or no change in well-being. For poorer countries, however, there is a clear impact of income on happiness. Once a country has over about $15,000 pc, its level of happiness appears to be independent of its income per head.

Fig. 7 images another interesting point. Obviously, some societies do a better job of maximizing their citizens' SWB than others. Latin American countries show higher levels of SWB than their economic and human development levels would predict. Conversely, the ex-communist societies showed lower levels of SWB than their economic and human development levels would predict. Thus, Fig. 7 tells us not only something about economics but also something about politics. The collapse of the political, economic and belief systems in the Soviet Union has sharply reduced the SWB in the ex-communist societies. The Soviet Union once played a prominent role in the world, which may have brought feelings of pride and satisfaction to many of their citizens.

The strong spreading of the data given in Fig. 7 reflects that happiness and life satisfaction are obviously also strongly influenced by other factors (e.g. security of crime, national myth and level of democracy). This is underlined in Fig. 8 showing the plot of the subjective well-being index versus the human development index, which can be regarded as some kind of "objective" well-being index. As outlined before, some countries fall below or are above the indicated trend line that represents a strong linear relationship of SWB and HDI, i.e. the population is unhappier or happier than that predicted by the average level of human development.

Fig. 9 shows the subjective well-being index (SWB) versus the primary energy consumption per capita. This leads to a similar correlation as the plots of GNP and HDI versus energy consumption (Figs. 3 and 6, respectively).

Fig. 9 indicates that about 2 toe pc is annually needed to make people happy. If more energy is consumed, this brings no or little further improvement in well-being, but there are again substantial differences from this trend in the ex-communist countries (less happy) and in Latin America where people are happier than their energy demand would predict.

To take stock: All indicators of prosperity, welfare and happiness (status of undernourishment, GNP, HDI and SWB) show that not more than an annual energy consumption of about 2 toe pc is needed to ensure at least a sufficiently high standard of living. A similar value of 2.5 toe pc is given by Smil (2003) after

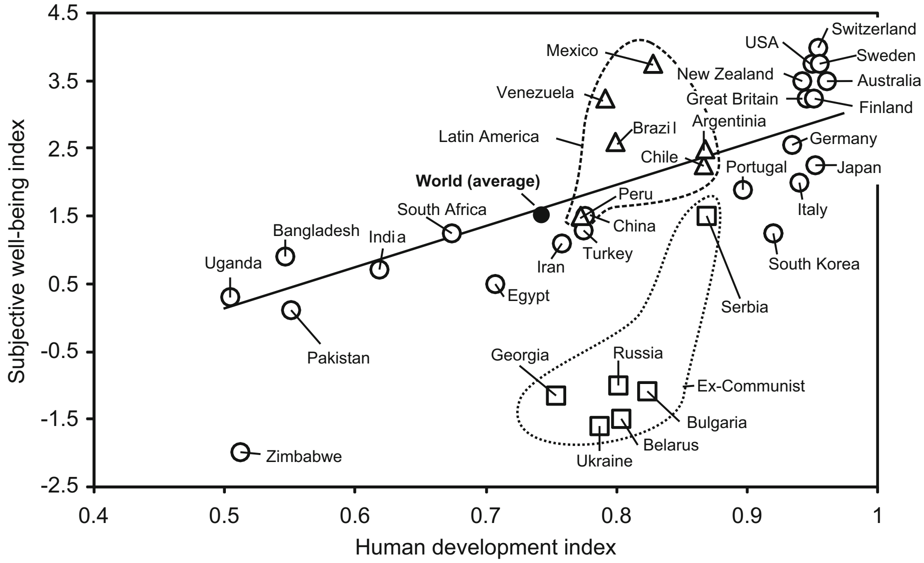

Fig. 8. Subjective well-being index (SWB) in the period 1995–2007 versus human development index (HDI) in 2007 (SWB data from Inglehart et al. (2008)).

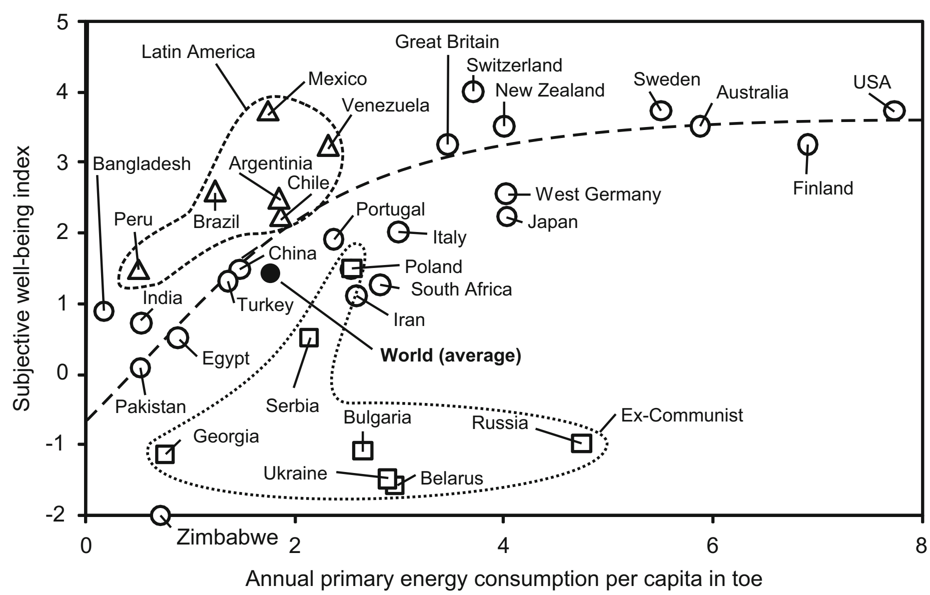

Fig. 9. Subjective well-being index (SWB) in the period 1995–2007 versus primary energy consumption per capita in 2007.

careful consideration of HDI, life expectancy and infant mortality. Consequently, it is to say that the quest for ever higher energy use has no justification either in objective evaluations or in subjective self-assessments.

Although this "critical" value of 2 toe pc and per year seems to be relatively low compared to current values in OECD countries in a range of 4–8 toe (pc and year), this value is justified as a good estimation of the future power for a, say, European standard of living as we have to consider that the energy consumption can be most probably reduced significantly by using more efficient technologies for transport, heating and electricity. Here are only some examples:

- Electrical engines (hopefully based on non-fossil electricity) are up to four times more efficient than petrol engines, and future public transport (also largely electrified) will be better integrated and better patronised (MacKay, 2008).
- The energy consumption of heating can be reduced by improved insulation and better control of temperature. According to Cremer et al. (2001), the possible savings by improved thermal protection of residential buildings in Germany are estimated to about 70%.
- The electricity network can be modernised by smart grids that delivers electricity from suppliers to consumers using digital technology to control appliances at consumer's homes to save energy. Smart meters in homes, businesses and public buildings would report to the electric companies at what time and how much energy is used. By charging more for electricity that is used during peak hours (of late afternoon and early evening) and by giving discounts during the low demand hours consumers would be forced to save energy by using as little as possible during peak hours, e.g. a washing machine could be programmed to only turn on when electricity demand is lowest. This would reduce the costs to meet peak demand by peak power plants and reduce the electricity demand by up to

10% (Kannberg et al., 2003). End of October 2009, President Obama announced that the Department of Energy will provide 3.4 billion $ to modernise the US electric grid.

Thus, an annual power consumption of 2 toe pc could be in future equivalent to 4 toe needed today to reach the current European standard of human development (Fig. 6) and subjective well-being (Fig. 9). Let us hope that the following quotation of Mahatma Gandhi is unfounded. "Earth provides enough to satisfy every man's need, but not every man's greed".

10. Energy consumption and ecological footprint

The ecological footprint is a measure of human demand on the Earth's ecosystems. It compares the demand with planet Earth's ecological capacity to regenerate, and represents the amount of biologically productive land and sea area needed to regenerate the resources the human population consumes. Using this assessment, it is possible to estimate how much of the Earth (or how many planet Earths) it would take to support humanity if everybody in the world would live a given lifestyle in a certain country. There are differences in the methodology used by various studies, e.g. how the sea area should be counted or how to account for fossil fuels and nuclear power. According to the Global Footprint Network (2009), the ecological footprint is defined as the sum of the area of all cropland, grazing land, forest, build-up land and fishing grounds required to produce food, fibre, timber, etc., and of the carbon (CO_2) footprint that represents the biocapacity needed to absorb CO_2 emissions. In 2005, the total global footprint was 17.5 billion global hectares (gha) or 2.7 gha per head (a global hectare is a hectare with world-average ability to produce resources and absorb wastes). On the supply side, the total productive area was 2.1 gha pc. Thus, humanity's total ecological footprint equals 1.3 planet Earths. In other words, humanity uses ecological services 1.3 times as fast as the Earth can renew them (Global Footprint Network, 2009). This value has grown over time, 0.55 planet Earths in 1960, one planet Earth in 1985 and 1.2 planet Earths in 2000. Without counteractions, a value of three global Earths will be reached in 2050.

In 2005, the single largest demand humanity put on the biosphere was its carbon footprint (52%), followed by cropland (24%), grazing land (10%), forest (9%), build-up land, fishing grounds (3%) and build-up land (2%). Tables 13 and 14 show some data of the population and ecological footprint in important regions and selected countries.

Today, the United States and China have the largest total footprints, each using 21% of the planet's biocapacity, but China had a much smaller per person footprint. India's footprint is currently the next largest, although the per person footprint is only about 0.5 planet Earths.

Fig. 10 shows that the ecological footprint is strongly linked to energy consumption. As a rule of thumb, an increase of the primary energy consumption by 1.5 toe per capita increases the ecological footprint by one planet Earth (Fig. 10). In other words – as we only have one planet Earth, the maximum average annual energy consumption should only be 1.5 toe pc compared to today's value (2007) of 1.8 toe pc. Thus we have to reduce the global energy consumption by about 15% to keep our planet "happy" (at current technologies and fuel shares). But this is in future by far not sufficient. The world population will grow to 9 billion in 2050 compared to today's population of 6.8 billion, and thus we have to limit our annual energy consumption to around 1.1 toe pc. But this is in contradiction with the moral

Table 13
Population, total ecological footprint and footprint per person in 2005 in different regions (footprint data from Global Footprint Network, 2009).

Region	Population in billion	Total ecological footprint in billion gha	Ecological footprint per head in planet Earths
Africa	0.90	0.60	0.7
Middle East and Central Asia	0.37	0.84	1.1
Asia-Pacific	3.56	5.70	0.8
Europe (EU)	0.49	2.29	2.2
Europe (non-EU)	0.24	0.84	1.7
Latin America and the Caribbean	0.55	1.33	1.1
North America	0.33	3.04	4.4
World	6.48	17.5	1.3

Table 14
Population, total ecological footprint (absolute and relative to own biocapacity) and footprint per head in selected countries (Global Footprint Network, 2009).

Country	Population in Million (2005)	Total ecological footprint in billion gha (2005)	Ecological footprint (2005)	
			Per head in planet Earths[a]	Total footprint relative to own total biocapacity
USA	298	2.80	4.5	1.9
Australia	20	0.16	3.3	0.5
Japan	128	0.63	2.3	8.1
Germany	83	0.35	2.0	2.2
Russia	143	0.53	1.8	0.5
Mexico	107	0.36	1.6	2.0
Brazil	186	0.45	1.1	0.3
China	1323	2.78	1.0	2.5
Nigeria	132	0.17	0.6	1.4
India	1103	0.99	0.4	2.2
Congo	58	0.03	0.3	0.2
World	6476	17.5	1.3	

[a] Number of planet Earths, if everybody in the world would live the lifestyle of the named country.

philosophy and obligation to bring welfare and happiness to the greatest number of people, i.e. 2 toe per year and head are needed to reach the level of prosperity, welfare and happiness, which is today only realised in high-income countries (Figs. 3, 4, 6 and 9).

11. Energy plan to solve the conflict between stable ecosystems and stable societies

Thus, the question inevitably arises how to cut the Gordian knot of the conflict between a happy planet (stable ecosystems) and a happy world population (stable societies). For an answer, some (admittedly optimistic) assumptions and some estimations are needed:

- Most forecasts predict that the world population will continue to grow until 2050 and then peak at a population in a range of 8–10 billion. Here we use a value of 9 billion.
- High-income countries with currently more than 2 toe pc should reduce their energy consumption to this value that could be possible without considerable loss of welfare, whereas currently low-income countries develop and increase their consumption until 2 toe pc is reached (scenario of a happy world population).
- Compared to today (1.8 toe pc, 6.8 billion people), this scenario (2 toe pc, 9 billion people) leads to an annual consumption of 18 billion toe compared to today's value of 12 billion. Thus, at current technologies and fuel shares the ecological footprint would increase to about 2 planet Earths (18/12 × 1.3 planet Earths in 2005). This would be a real disaster!
- The only solution to implement an average energy consumption of 2 toe per head ("happy population") without increase in the ecological footprint ("happy planet") is to reduce the single largest demand humanity put on the biosphere, which is the carbon (CO_2) footprint with a share of currently 52% on the total ecological footprint. Only in case of a complete shift from fossil fuels to renewables (except of the small amount probably still needed for chemicals and coke/steel production, at least within the next decades, Table 14) would half the ecological footprint, and that is exactly what is needed to reach the desired footprint of one planet Earth.

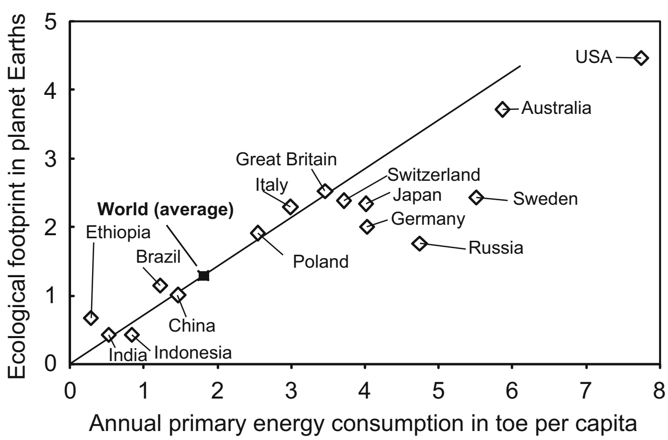

Fig. 10. Ecological footprint (per capita) and primary energy consumption per capita in selected countries (footprint data from Global Footprint Network, 2009).

Table 15 summarises what has to been done in this century with regard to energy demand to reach a happy planet (stable ecosystems) and a happy population (stable societies).

The comparison of current forecasts of the energy consumption and energy mix in 2100 (Schollnberger, 2006) with the goal to reconcile the world's unceasing demand for energy with the absolute necessity to preserve the integrity of the biosphere (Table 15) indicates that it will be a Herculean task to reach this goal, and that more and excellent scientists and engineers are needed. Although there is the possibility that some previously unheard technology may develop during the next decades, many steps are needed to change the current energy mix and to reduce the world's energy demand. Consequently, politicians should more than ever ensure framework requirements for an effective educational system and excellent conditions for (energy)

Table 15
Today's and future global primary energy consumption (data from IEA (2007, 2009), BP (2009) and from author's own estimates).

Energy type	World primary energy consumption in billion toe		
	Today (2007)	Forecast for 2100[a]	Happy planet (ecosystems) and happy world population (societies)
Crude oil	4.0	2.1	1.5[b] (production of chemicals and of blast furnace coke)
Coal	3.2	4.8	
Natural gas	2.5	2.8	
Traditional biomass (firewood)	0.8	0.7	–
Total fuels with CO_2 footprint	10.6	10.4	1.5
Nuclear	0.7[c]	7.0	? (for an attempt to an answer see Table 16)
Hydro	0.6[c]	1.3	
Commercial biomass	0.4	1.1	
Geothermal	0.2[c]	1.8	
Wind		2.8	
Solar		5.6	
Other		5[d]	
Total fuels with no or negligible CO_2 footprint	1.9	24.6	16.5
World energy consumption	12.4[c]	35	18 (=2 toe per head and per year)

[a] Data from Schollnberger (2006).
[b] 8% of the crude oil is used for petrochemicals (Moulijn et al., 2004), which equals currently about 0.3 billion tonnes. 0.6 billion tonnes of coal is currently used for coke (steel production). 0.1 billion tonnes of ethane (separated from natural gas) is used to produce ethylene, and about 0.1 billion tonnes of fossil fuels are needed for ammonia production. Thus (if we only count these major chemical products), with a rising world population (from 6.8 to 9 billion people), about 1.5 billion tonnes of fossil fuels would be needed for the chemical and metallurgical industry. At least, (organic) chemicals like polymers can be in principle also produced from renewables (e.g. via biomass gasification and subsequent Fischer–Tropsch synthesis to higher hydrocarbons), but this is not considered here.
[c] For non-fossil electricity, the "substitution equivalence method" is used.
[d] Waste incineration, hydrogen, oil shale, today unheard technology.

Table 16
Estimation of the technically feasible potential of renewable energy in toe per capita and year (data from MacKay, 2008) and two energy plans for a world population of 9 billion.

Energy source	Energy potential and consumption (goal) in toe per capita	
	Potential[a] (estimation based on data from MacKay)	Scenario for a happy planet and a happy world population (2 toe per capita and year)
Wind	0.5	0.2[b]
Hydro	0.13	0.07[c]
Tide and wave	0.02	0.01
Geothermal	0.17	0.08
Total non-solar renewable energy	0.8	0.36
Solar for energy crops (biomass)	0.2[d]	0.1
Concentrated solar power[e]	6	1.54
Nuclear (once-through reactor)[f]	0.16	–
Nuclear (fast breeder)[f]	9.5	–

[a] Here we use the direct equivalence method because in an alternative world with relatively plentiful electricity and little oil, gas and coal, we do not use fossil fuels anymore to produce electricity, and we might even use electricity to produce chemicals. The timeless and scientific way to summarise and compare energy is then a one to one conversion rate, i.e. 1 kJ of electricity is 1 kJ of chemical energy (MacKay, 2008).

[b] Although the technical feasible potential of wind energy is higher, the production of electrical power equivalent to 0.2 toe pc and year (2 TW) would already require the operation of 2 million state-of-the-art wind turbines.

[c] This value is considered to be economically feasible hydropower and is reached if the currently installed capacity is increased by a factor of about 2.5 (MacKay, 2008).

[d] Even the theoretical potential of energy crops, if all currently arable or cropland (27 million km^2) would be used, is only about 0.8 toe per capita and year (world population of 9 billion, 33% losses in processing and farming, MacKay, 2008). This number has of course by far not been reached, as we need agricultural land for food production. According to Heinloth (2003), the technical feasible potential of commercial biomass for heat (20%), fuels (25%) and electricity (55%) is in total about 0.2 toe per capita and year.

[e] According to the DESERTEC plan, the use of concentrated solar power in sunny Mediterranean countries, and high-voltage direct-current transmission lines could deliver power to cloudier northern parts of Europe. The economic potential adds up 50 billion toe electricity (=6 toe per capita and year for a global population of 9 billion). It is also assumed that mirrors will remain cheaper than photovoltaic panels (MacKay, 2008), i.e. photovoltaic energy systems are neglected.

[f] Assumption that not only mined uranium can be used but also the uranium extracted from oceans, which is 98% of total uranium (MacKay, 2008). It is far beyond the scope of this paper to comment on risks of nuclear energy and the breeder technology.

research. At present, there are not much signs that politicians and societies are changing as it is needed to reach this goal, but the pressure will increase heavily to do so in the decades that are ahead of us.

What are the alternatives that we have to reach the goal of 2 toe per capita and year? Table 16 shows an estimation of the technical feasible potential of renewable energy in toe per capita and year for a world population of 9 billion based on the data given by MacKay (2008).

There is one clear conclusion: the non-solar renewables may be huge, but they are by far not huge enough. Even the technically feasible potential of wind, hydro, tide, wave and geothermal energy would only cover 0.8 toe per capita and year compared to the goal of at least 2 toe. To complete an energy plan that adds up, we must rely on one or more forms of solar power, or we use nuclear power or both.

One scenario (out of many one may think of) of a sustainable non-nuclear energy plan is given in the right column of Table 16. It was thereby assumed that only about 50% of the technically feasible potential of solar power from energy crops and of wind, hydro, tide, wave and geothermal power will be used as this reflects better the economically visible potential (see footnotes of Table 16). Thus about three quarter of the energy demand has to be covered by concentrated solar power.

In principle, it should also be possible not only to produce electricity from solar energy. Also "solar" methanol and other "solar" fuels like gasoline and diesel fuels can be produced with no or much less net CO_2-production compared to fossil fuels by the following steps (Behr et al., 2009; Centi and Perathoner, 2009; Saito et al., 2000; Wolf and Scheer, 2005):

(1) Separation of CO_2 from flue gases (or even from the atmosphere),
(2) hydrogen production by water electrolysis and non-fossil electricity ($H_2O \rightarrow H_2 + ½O_2$),
(3) CO production by reverse water gas shift ($CO_2 + H_2 \rightarrow CO + H_2O$), and finally
(4) synthesis of gasoline/diesel oil or methanol synthesis ($CO + 3H_2 \rightarrow -(CH_2)- + H_2O$ or $CO + 2H_2 \rightarrow CH_3OH$).

12. Summary

Based on indexes that characterise prosperity, undernourishment, welfare and happiness as well as the ecological footprint as a measure of human demand on the Earth's ecosystems the following conclusions can be drawn.

The scenario of a happy world population at minimum energy consumption implies two essential actions:

(1) High-income countries with a current energy demand in the range of 3–8 tonnes of oil equivalent per capita (toe pc) have to reduce their demand – partly drastically – to about 2 toe pc. This value is most probably still sufficient without cutback in welfare and happiness, and should therefore be taken as the target. The quest for ever higher energy use has no justification either in objective evaluations or in subjective self-assessments.
(2) Vice versa, currently low-income countries should develop and increase their energy consumption until 2 toe pc is reached.

Compared to today (1.8 toe pc global average, 6.8 billion people) this scenario (2 toe pc, 9 billion people) would lead to an annual energy consumption of 18 billion toe compared to currently 12 billion. In today's technologies and fuel shares this would lead to an inadmissible increase of the ecological footprint from today's 1.3 planet Earths (already 30% too much) to two planet Earths.

The only solution to provide globally an average energy consumption of 2 toe pc (needed for a happy world population) without increasing the ecological footprint is a strong reduction of the single largest demand humanity put on the biosphere, which is the carbon (CO_2) footprint with a share of 50% on the ecological footprint. In the ideal case – hopefully reached until 2100 – a complete shift from fossil fuels to renewables would half the ecological footprint, and that is exactly what is needed to reach the desired footprint of one planet Earth. To reach this goal, we must rely on solar power and/or nuclear power as the non-solar renewables are not huge enough.

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