Climate change and the complexity of solutions for securing energy supply: the global Energy [R]evolution

Fulcieri Maltini*

FM Consultants Associates, France

The impact of greenhouse emissions on climate change and the decrease in world fossil energy sources will have significant consequences for the future of the planet. Three major reports ("The Stern Review: the Economics of Climate Change", October 2006; "Where Will the Energy for Hydrogen Production Come From? Status and Alternatives" by Ludwig-Bolkow-Systemtechnik GmbH—LBST/European Hydrogen Association, 2007; and an updated version of "The Global Energy (R)evolution Scenario" by GWEC-EREC-Greenpeace International, 2013) are analysed in this review. Additional data are supplied by the Intergovernmental Panel for Climate Change (IPCC) report (2013) and its addendum presented in March 2014. They reach the same conclusions about the complexity of the phase-out from the carbon society and the conversion to energy efficiency and renewable energy sources.

1. Greenhouse emissions and climate change

Over the last century humankind has rescripted its role in the natural world. Millions upon millions of people have been fed, many deadly diseases have been treated, technology has taken us into space, and given us telecommunications and the Internet-run society. Much of nature has been bent to our will, but still it appears difficult to deal with the weather. For many years, it was believed that climate changes were caused by solar influence and cosmic radiation.[1] Now, in the face of disastrous flooding, the melting of glaciers and the threat of disappearance of entire islands and considerable degradation of the ecosystem, a different reality has appeared. A significant body of scientific evidence seems to indicate that the Earth's climate is rapidly changing possibly as a result of increases in greenhouse gases caused by human activities.

* E-mail: fulcierimaltini@gmail.com

1 M. Lockwood and C. Fröhlich, Recent oppositely directed trends in solar climate forcings and the global mean surface air temperature. *Proc. R. Soc. A* **463** (2007) 2447–2460.

Nanotechnology Perceptions **10** (2014) 100–141
Received 17 July 2014

Since the close of the pre-industrial era (around 1800), atmospheric carbon dioxide, methane and nitrous oxide concentrations[2] have increased, mainly as a result of human activities burning fossil fuels, and deforestation and other changes in land-use. Figure 1 shows greenhouse gas (GHG) emissions in 2000 by sector.

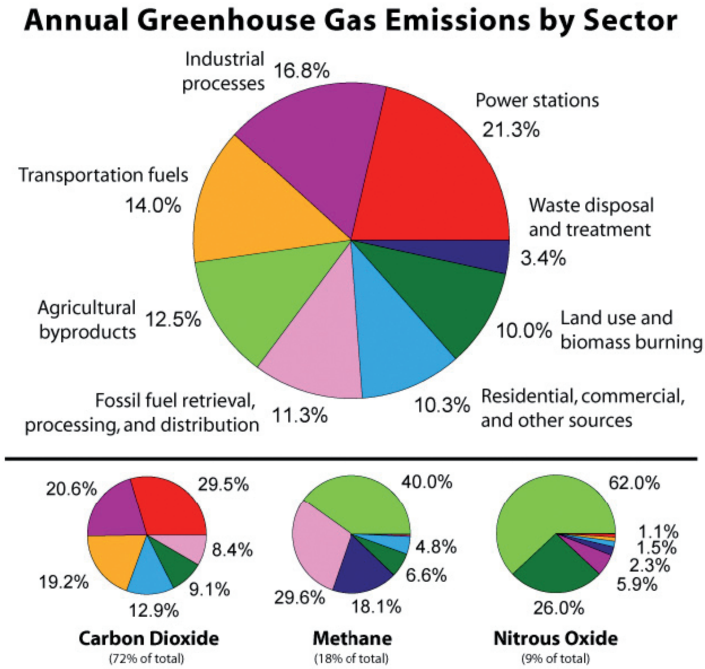

Figure 1. Annual greenhouse gas (GHG) emissions by sector (source: IPCC 2004).

The Earth's climate system is a complex structure, which is driven by interactive natural and human activities. Figure 2 shows a flowchart representing world GHG emissions and their origins, and Figure 3 shows most of the components and their interactions.

There is compelling evidence that the worldwide rising levels of greenhouse gases will have a warming effect on the climate. Figure 4 shows the annual emissions from 1970 to 2010. The result is an increase of the amount of infrared radiation (heat energy) reflected by the earth and trapped by the atmosphere, which is in effect thickening: this is the "greenhouse effect" as shown in Figure 5.

2 Carbon dioxide (CO_2) is the primary greenhouse gas (GHG) emitted through human activities. In 2012, CO_2 accounted for about 84% of all greenhouse gas emissions. Carbon dioxide is naturally present in the atmosphere as part of the Earth's carbon cycle (the natural circulation of carbon among the atmosphere, oceans, soil, plants and animals). Human activities are altering the carbon cycle—both by adding more CO_2 to the atmosphere and by influencing the ability of natural sinks, like forests, to remove CO_2 from the atmosphere. While CO_2 emissions come from a variety of natural sources, human-related emissions may be responsible for the increase that has occurred in the atmosphere since the Industrial Revolution. Besides CO_2, however, GHG include, at equilibrium, other gases of which the major are CH_4 (methane), N_2O (nitrous oxide), O_3 (ozone), CFCs (chlorofluorocarbons), PFCs (perfluorocarbons), HFCs (hydrofluorocarbons) and SF_6 (sulfur hexafluoride). To simplify, in this text we will denominate as CO2e the CO_2 equivalent, with respect to the greenhouse effect, of all GHG.

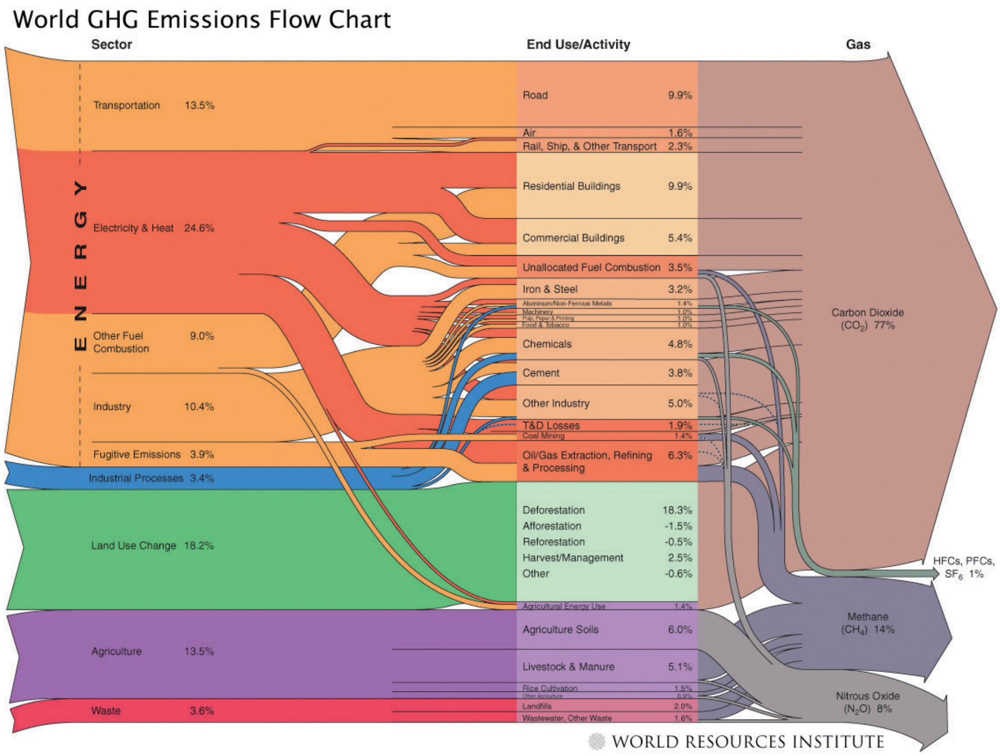

Figure 2. World GHG emissions flow chart (source: World Resources Institute, 2009).

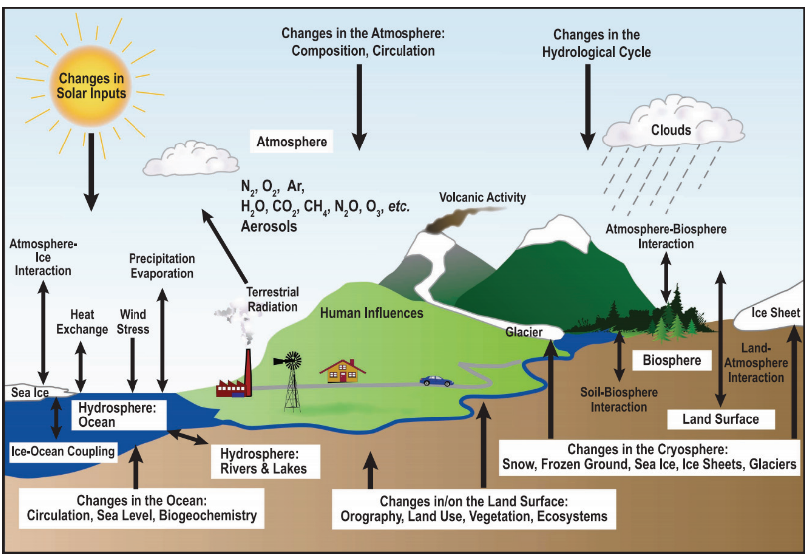

Figure 3. Schematic view of the components of the climate system, their processes and interactions (source: IPCC, 2007: *The Physical Science Basis. Contribution of Working Group 1 to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*).

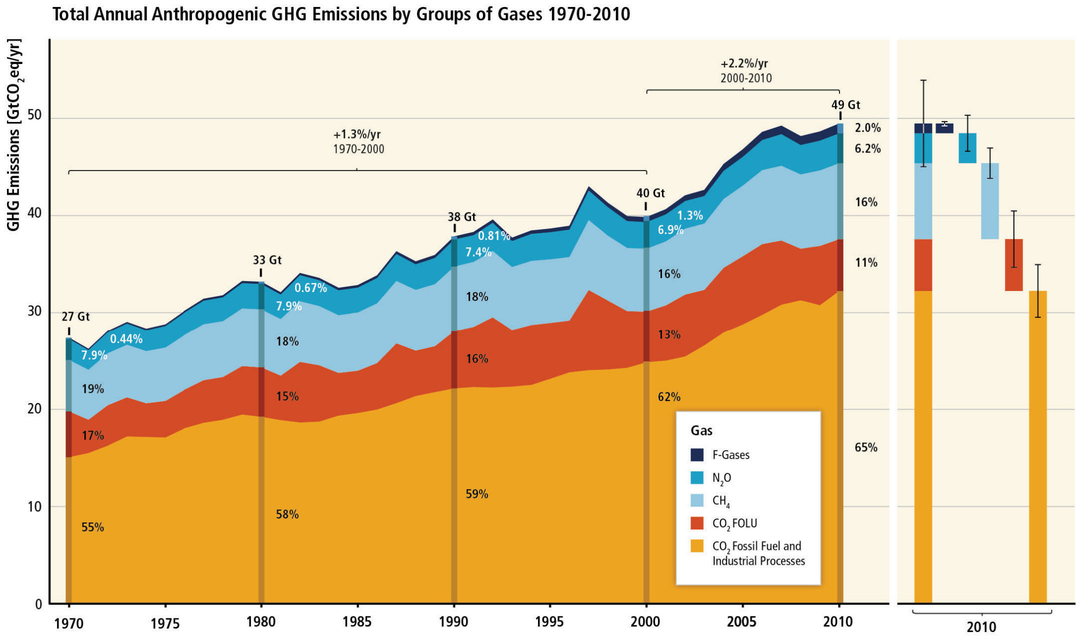

Figure 4. Annual GHG emissions by groups of gases (source: IPCC, 2014).

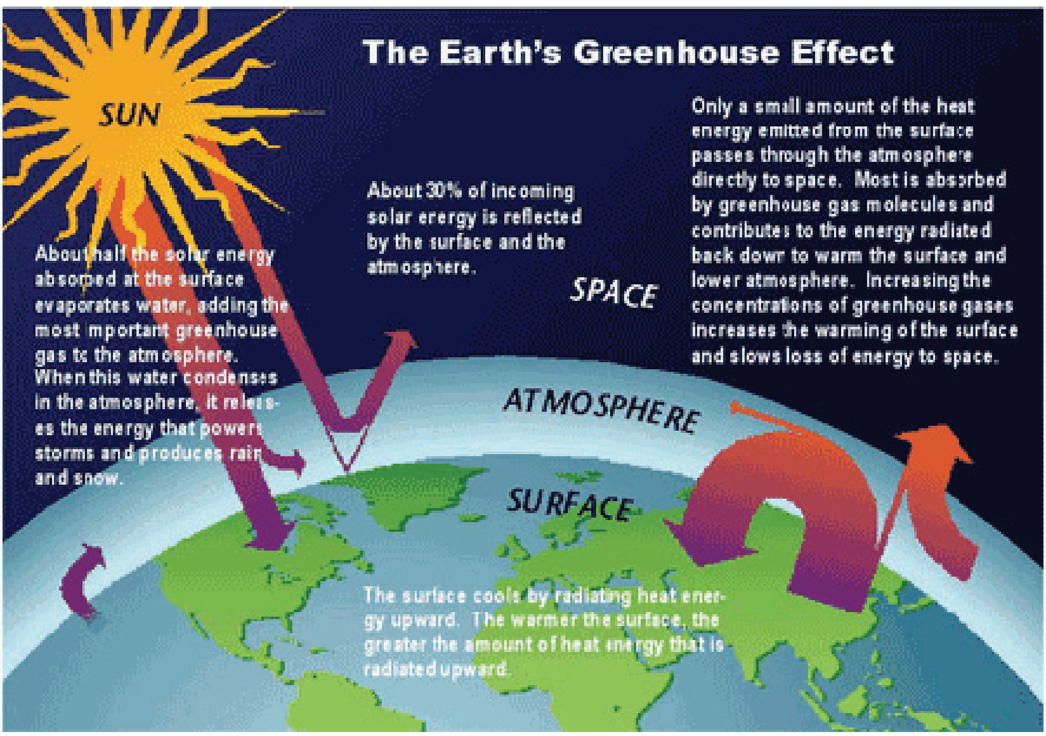

Figure 5. The greenhouse effect (source: US Global Change Research Program—USGCRP).

Figure 6 shows the growing trend of cumulative CO2e emissions since 1970; Figure 7 shows the global warming potential (GWP) values and lifetimes in years of major gases—as the base from which all other greenhouse gases are compared (carbon dioxide has a GWP of 1).

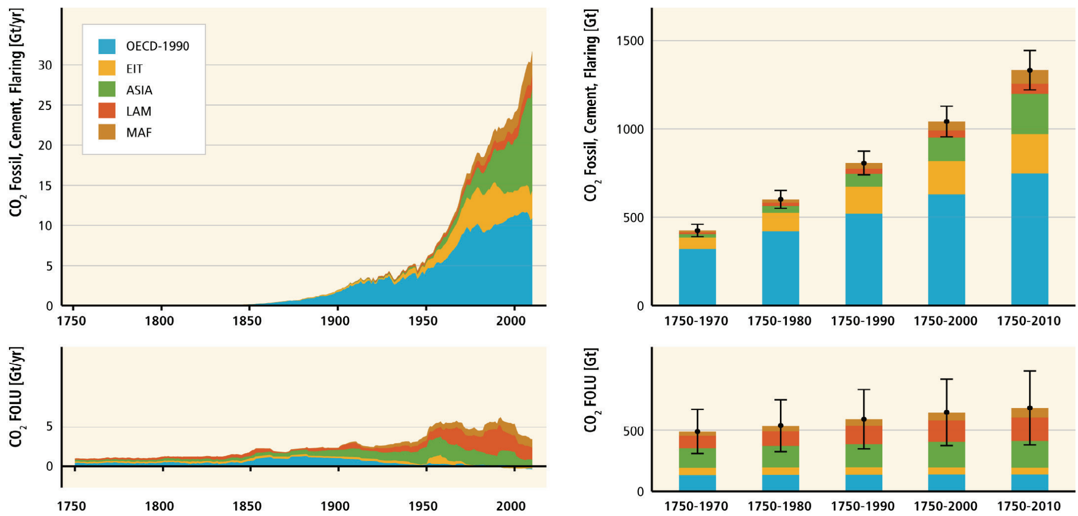

Figure 6. Cumulative CO2e emissions have more than doubled since 1970 (source: IPCC, 2014, Working Group III).

GWP values and lifetimes from 2013 IPCC AR5 p714 (with climate-carbon feedbacks) [6]	Lifetime (years)	GWP time horizon	
		20 years	100 years
Methane	12.4	86	34
HFC-134a (hydrofluorocarbon)	13.4	3790	1550
CFC-11 (chlorofluorocarbon)	45.0	7020	5350
Nitrous oxide	121.0	268	298
Carbon tetrafluoride (CF_4)	50000	4950	7350

Figure 7. Global warming potential (GWP) values and lifetimes in years of major gases. Carbon dioxide is the base from which all other greenhouse gases are compared (source: IPCC 2013).

Figure 8 illustrates the types of impact that could be experienced as the world comes into equilibrium with more greenhouse gases.[3] The top panel shows the range of temperatures projected at stabilization levels between 400 ppm (parts per million) and 750 ppm CO2e. The prominent vertical line on each range indicates the mean of the 50th percentile point. The solid horizontal lines indicate the 5–95% ranges based on climate sensitivity estimates from the IPCC 2001 report and the Hadley Centre ensemble study. The dashed horizontal lines show the 5–95% ranges based on eleven recent studies. The bottom panel illustrates the range of impacts expected at the different levels of warming. The relationship between global average temperature changes and regional climate changes is very uncertain, especially with regard to changes in precipitation.

[3] *The Economics of Climate Change: the Stern Review*. Cambridge: University Press (2007).

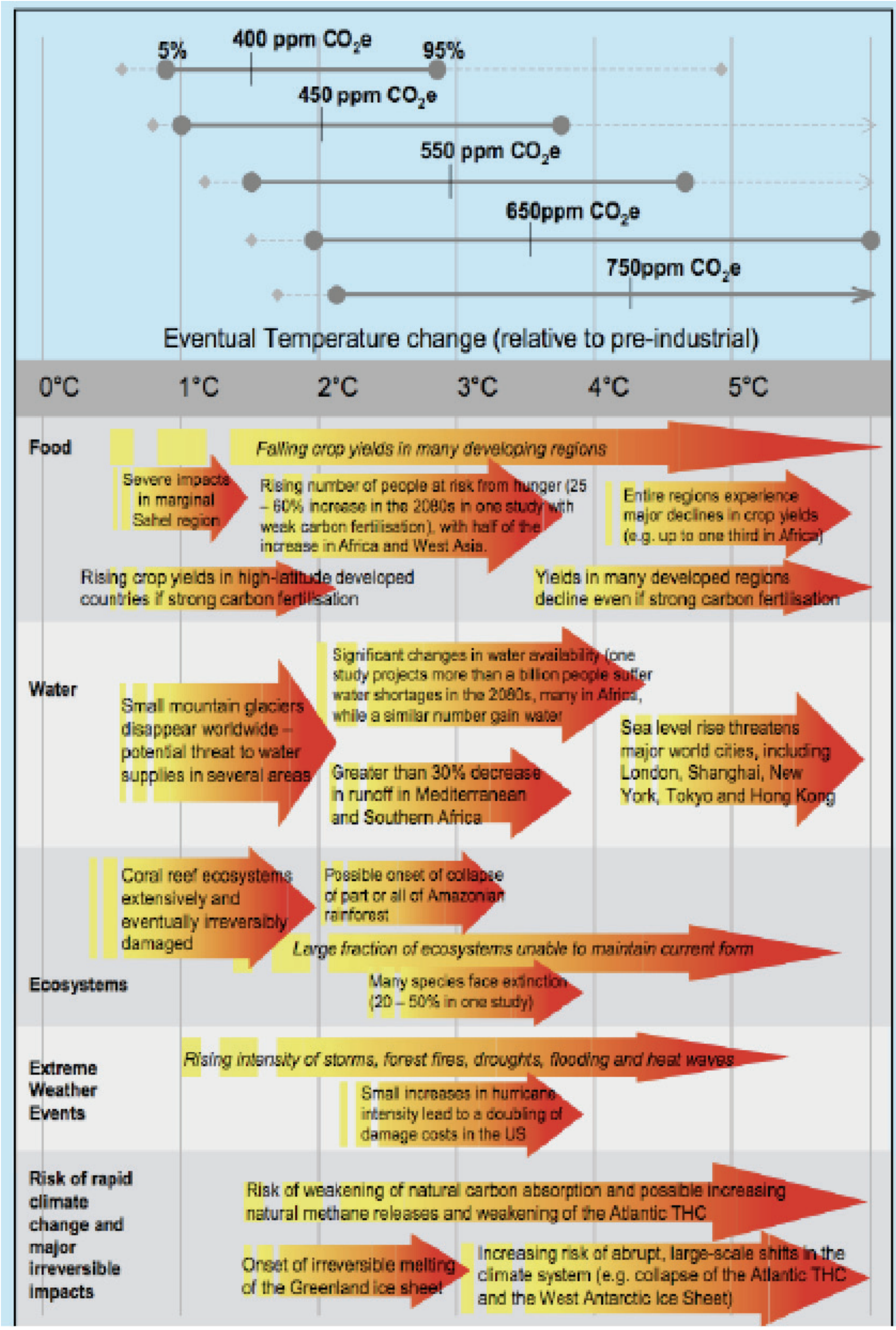

Figure 8. Stabilization levels and the types of impact that could be experienced as a function of the increase of CO2e and temperature (source: *The Economics of Climate Change: The Stern Review*. Cambridge: University Press, 2007).

The current level or stock of greenhouse gases in the atmosphere is today equivalent to around 380 ppm CO2e compared with only 280 ppm before the Industrial Revolution. This concentration has already caused the world to warm by more than 0.5 °C and will lead to at least a further half degree of warming over the next few decades because of inertia in the climate system.

The change in global average near-surface temperature between 1850 and 2005 has been on a rising trend, as shown in Figure 9. Recent modelling by the Hadley Centre and other research institutes show that the observed trends in temperatures at the surface and in the oceans, as well as the spatial distribution of warming, cannot be replicated without the inclusion of both human and natural effects. Taking into account the rising levels of aerosols, which cool the atmosphere, and the observed heat uptake by the oceans, the calculated warming effect of greenhouse gases is more than enough to explain the observed temperature rise.

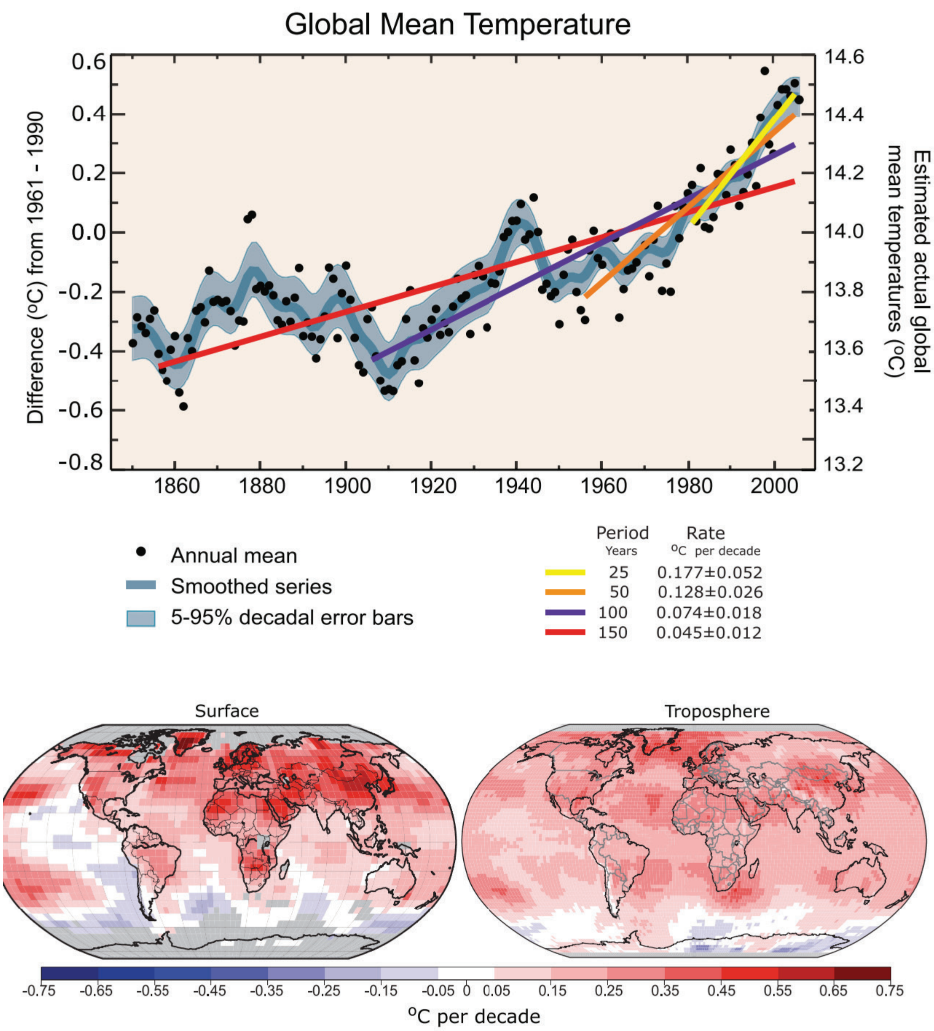

Figure 9. Annual global mean observed temperatures (source: IPCC, 2007: *The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report*).

Stabilization at 450 ppm CO2e is already almost out of reach, given that we are likely to reach this level within ten years and that there are real difficulties in making the sharp reductions required with current and foreseeable technologies. The cost of stabilizing CO2e levels at 550 ppm is estimated at 300 million euros/year, which is equivalent to 1% of global GDP.[3] In fact, the annual flow of emissions is accelerating, as fast-growing developing economies invest in high-carbon infrastructure and as demand for energy and transport increases around the world.

Figure 10 shows the link between greenhouse emissions and climate change. The Arctic has been predicted to be hit first by global warming, principally because warming at the northern pole is enhanced by positive feedback: snow and ice reflect 80% to 90% of solar radiation back into space, but when these white surfaces disappear, more solar radiation is absorbed by the underlying land or sea as heat. This heat, in turn, melts more snow and ice. A major consequence is considerable melting of the Greenland ice sheet which, in turn, will affect ocean circulation due to diminishing salt concentration in the sea. Warming will have many additional severe impacts, often mediated through water:

- Widespread thawing of permafrost regions is likely to add to the extra warming caused by the weakening of carbon sinks. Large quantities of methane (and carbon dioxide) could be released from the thawing of permafrost and frozen peat bogs. For example, it is estimated that if all the carbon accumulated in peat alone since the last Ice Age were released into the atmosphere, this would raise greenhouse gas levels by 200 ppm CO2e.
- Melting glaciers will initially increase flood risk and then strongly reduce water supplies, eventually threatening one-sixth of the world's population, predominantly in the Indian subcontinent, parts of China, and the Andes in South America.
- Declining crop yields, especially in Africa, could leave hundreds of millions without the ability to produce or purchase sufficient food. At mid to high latitudes, crop yields may increase for moderate temperature rises (2–3 °C), but then decline with greater warming. At 4 °C and above, global food production is likely to be seriously affected.
- At higher latitudes, cold-related deaths will decrease, but climate change will increase worldwide deaths from malnutrition and heat stress. Vector-borne diseases such as malaria and dengue fever could become more widespread if effective control measures are not in place.
- Rising sea levels will result in tens to hundreds of millions more people experiencing floods each year with warming of 3 or 4 °C. There will be serious risks and increasing pressures for coastal protection in south-east Asia (Bangladesh and Vietnam), small islands in the Caribbean and the Pacific, and large coastal cities such as Tokyo, New York, Cairo and London. According to one estimate, by the middle of the century 200 million people may become permanently displaced due to rising sea levels, heavier floods and more intense droughts.
- Ecosystems will be particularly vulnerable to climate change, with around 15–40% of species potentially facing extinction after only 2 °C warming. Ocean acidification, a direct result of rising carbon dioxide levels, will have major effects on marine ecosystems, with possible adverse consequences on fish stocks. Higher temperatures will increase the chance of triggering abrupt and large-scale changes.
- Warming may induce sudden shifts in regional weather patterns such as the monsoon rains in southern Asia or the El Niño phenomenon, changes that would have severe consequences for

water availability and flooding in tropical regions and threaten the livelihoods of millions of people.

- A number of studies suggest that the Amazon rainforest could be vulnerable to climate change, with models projecting significant drying in this region. One model, for example, finds that the Amazon rainforest could be significantly, and possibly irrevocably, damaged by a warming of 2–3 °C.

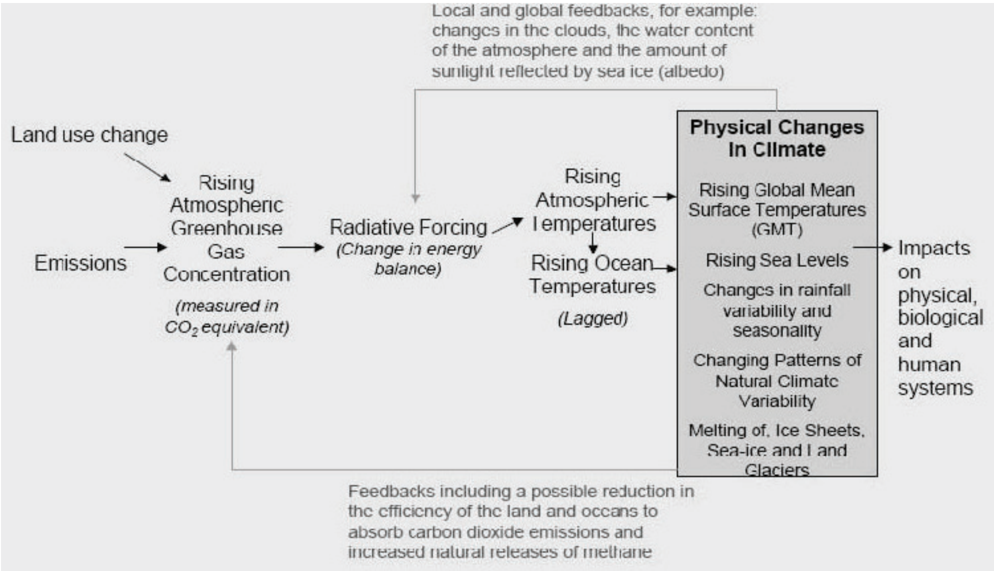

Figure 10. The link between greenhouse emissions and climate change.

A dramatic presumed example of the effect of global warming is given in the Figure 11 photographs of the Upsala glacier in Patagonia taken in 1928 and 2004.

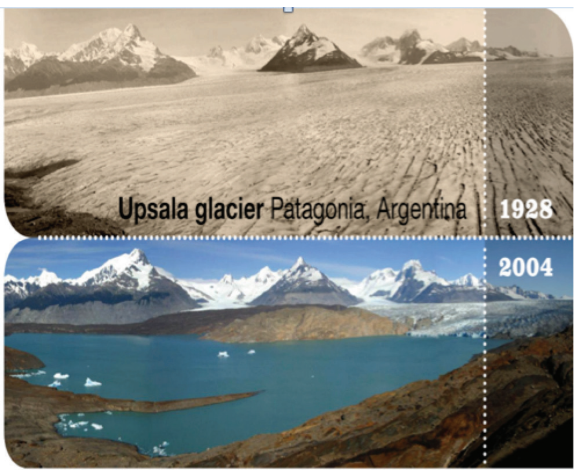

Figure 11. The Upsala glacier in Patagonia in 1928 (upper) and 2004 (source: Greenpeace).

The risks of serious, irreversible impacts from climate change increase strongly as concentrations of greenhouse gases in the atmosphere rise. Dr R.K. Pachauri, Chairman of the IPCC, stated in January 2007:

> There is now growing awareness on the imperatives for a global energy future which marks a distinct departure from past trends and patterns of energy production and use. These imperatives emerge as much from the need to ensure energy security, as they do from the urgency of controlling local pollution from combustion of different fuels and, of course, the growing challenge of climate change, which requires reduction in emissions of greenhouse gases particularly carbon dioxide. The scientific evidence on the need for urgent action on the problem of climate change has now become stronger and convincing. Future solutions would lie in the use of existing renewable energy technologies, greater efforts at energy efficiency and the dissemination of decentralised energy technologies and options.

In response to the climate change threat, the Kyoto Protocol has committed its signatories to reducing their GHG emissions by 5.2% from their 1990 level during the target interval of 2008–12. This, in turn, has resulted in the adoption of a series of regional and national reduction targets. In the European Union, for instance, the commitment is to an overall reduction of 8%. In order to reach this target, the EU has agreed to increase its proportion of renewable energy from 6% to 20% by 2020. The Kyoto Protocol includes "flexible mechanisms", which allow economies to meet their GHG emission limit by purchasing GHG emission reductions from elsewhere. These can be bought either from financial exchanges, or from projects that reduce emissions in developing economies under the Clean Development Mechanism (CDM).

The Kyoto signatories will define new targets in 2015. It is urgent that industrialized countries reduce their CO2e emissions by 18% from 1990 levels, and then by 30% between 2018 and 2022. Only with these cuts do we stand a reasonable chance of keeping the average increase in global temperatures to less than 2 °C, beyond which the effects of climate change will probably become catastrophic. Unfortunately, among the 169 countries and other governmental entities that have ratified the agreement (representing over 60% of emissions from major countries), notable exceptions include the United States of America, Canada and Australia, all significant emitters.

The new 2013–14 IPCC report shows that global emissions of greenhouse gases have risen to unprecedented levels, despite a growing number of policies to reduce climate change. Emissions grew more quickly between 2000 and 2010 than in each of the three previous decades.

The report has evidenced that:

- Reaching 450 ppm CO2e entails consumption losses of 1.7% (1%–4%) by 2030, 3.4% (2% to 6%) by 2050 and 4.8% (3%–11%) by 2100 relative to the baseline (which grows between 300% to 900% over the course of the century).
- This is equivalent to a reduction in consumption growth over the 21st century by about 0.06 (0.04–0.14) percentage points a year (relative to annualized consumption growth that is between 1.6% and 3% per year).
- Estimates of the economic costs of mitigation vary widely. In business-as-usual scenarios, consumption grows by 1.6 to 3% per year. Ambitious mitigation would reduce this growth by around 0.06 percentage points a year. However, the underlying estimates do not take into

account economic benefits of reduced climate change; that is, the estimates exclude benefits of mitigation (reduced impacts from climate change). They also exclude other benefits such as improvements in local air quality.

The report asserts that it would be possible, using a wide array of technological measures and changes in behaviour, to limit the increase in global mean temperature to 2 °C above pre-industrial levels. However, only major institutional and technological change will give a better-than-even chance that global warming will not exceed this threshold.

The report stresses that *mitigation* has become an absolute requirement that all countries should put in place. Delaying mitigation is estimated to increase the difficulty and narrow the options for limiting warming to 2 °C. Without more mitigation, global mean surface temperature might increase by 3.7 ° to 4.8 °C over the 21st century. This is illustrated in Figures 12 and 13.

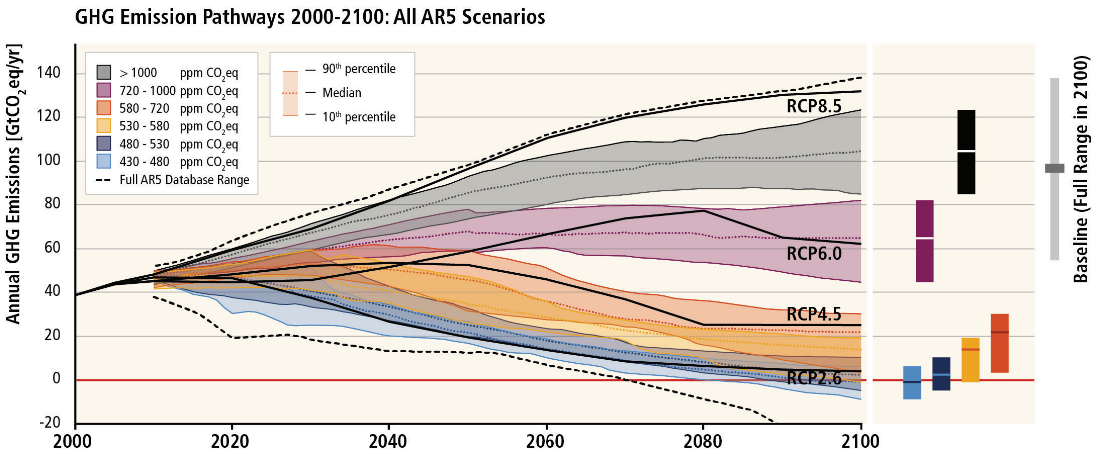

Figure 12. Scenarios showing variation of temperature as a function of GHC emissions. (source: IPCC Working Group III, 2014[4]).

Costs rise significantly as mitigation efforts become more ambitious or sudden. Delay in taking action on climate change would make it necessary to accept both more climate change and, eventually, higher mitigation costs. Weak action during the next 10–20 years would put stabilization even at 550 ppm CO2e beyond reach—and this level is already associated with significant risks. The level of 550 ppm CO2e could be reached as early as 2035. At this level, there is at least a 77% chance, and perhaps up to a 99% chance, depending on the climate model used, of global average temperature rise exceeding 2 °C.

The Economics of Climate Change: the Stern Review,[3] published in 2007, evidenced that the cost of stabilizing CO2e levels at 550 ppm is 300 million euros/year, which is equivalent to 1% of global GDP, and opined that "this cost will be multiplied by 3–4 by 2050 if action is not taken today". Further, the Stern Review estimated that "if we don't act, the overall costs and

4 *Climate Change 2014: Mitigation of Climate Change*, www. http://mitigation2014.org/ is the third of three Working Group reports which, along with a Synthesis Report due in October 2014, constitute the 2014 IPCC's fifth assessment report on climate change.

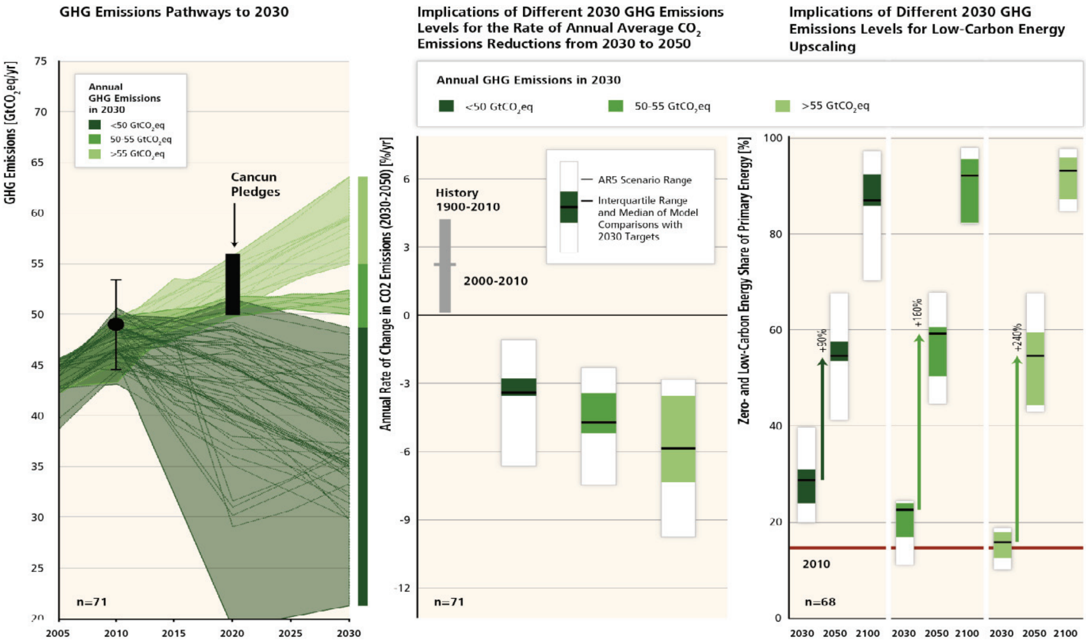

Figure 13. Consequences of delays in mitigation (source: IPCC Working Group III, 2014).

risks of climate change will be equivalent to losing at least 5% of global GDP each year, now and forever. If a wider range of risks and impacts is taken into account, the estimates of damage could rise to 20% of GDP or more." The Review goes on to assert: "In contrast, the costs of action—reducing greenhouse gas emissions to avoid the worst impacts of climate change—can be limited to around 1% of global GDP each year." These statements have been bolstered by the IPCC 2013–14 report.

The investment that takes place in the next 10–20 years will have a profound effect on the climate in the second half of this century and in the next. "Our actions now and over the coming decades could create risks of major disruption to economic and social activity, on a scale similar to those associated with the great wars and the economic depression of the first half of the 20th century. And it will be difficult or impossible to reverse these changes."[5]

2. Primary energy resources

Alongside global warming, other challenges have become just as pressing. The global population on the planet is generally predicted to increase, by 2050, from 6.3 to 8.9 milliard individuals. Worldwide energy demand is growing at a staggering rate. Overreliance on energy imports from a few, often politically unstable, countries and volatile oil and gas prices have together pushed security of energy supply to the top of the political agenda, as well as threatening to inflict a massive drain on the global economy. But whilst there is a broad consensus that we need to change the way we produce and consume energy, there is still disagreement about how

[5] "The Global Energy (R)evolution Scenario", EREC—Greenpeace International, 2007.

to do it. Meanwhile, a fundamental question has been repeatedly asked: “where will our energy come from in the coming decades?”

Today it mainly comes from finite fossil fuel; in the long term, it will have to come from renewable energies. The basic questions of availability of raw energy, the impact on the environment (which gravely affects the planet) by the use of fossil fuels, and the solution we can bring to preserve our future will be answered in this paper. To do this, it is first necessary to clarify how long production rates can follow and meet the growing demand for crude oil, natural gas and coal. Furthermore, particularly for coal, we need to understand whether, to what extent and over what period of time the separation and safe storage of carbon dioxide from burning fossil fuels is possible (it has not yet been safely proven). It is a basic requirement for carbon-based energy production. We also need to explore what alternatives could exist for converting CO2e into something harmless.

Concern regarding security of supply is focused both on price security and the security of physical supply. At present around 80% of global energy demand is met by fossil fuels. The unrelenting increase in energy demand is incommensurate with the finite nature of fossil fuel sources. Furthermore, the regional distribution of oil and gas resources does not match the distribution of demand; some countries have to rely almost entirely on fossil fuel imports.

3. The fossil fuels

3.1 Oil production

Oil is the life blood of the modern global economy, as the effects of the supply disruptions of the 1970s made clear. It is the number one source of energy, providing 36% of the world’s needs and is the fuel employed almost exclusively for essential uses such as transportation. However, a debate has developed over the ability of supply to meet increasing consumption, a debate obscured by poor information and stirred by recent soaring prices. Figure 14 shows the historic trend in world oil production and its probable development in the future. Production is almost at a peak and will clearly decrease in the coming decades—the maximum crude oil production (“Peak Oil”) represents a decisive turning point. Figures 14, 15 and 16 show oil production trends globally, by region and by country.

A multitude of evidence supports this thesis: since 1980 we have been using more oil than we find each year and the gap is growing ever larger. More and more production regions have already exceeded their maximum production. This applies in particular to all the large old fields, which still make a significant contribution to world oil production. There are also clear signs that the oil-rich countries of the Middle East and the countries of the former Soviet Union cannot further extend their production. This is all in the face of the expectation of a further increase in worldwide demand, as highlighted in the International Energy Agency World Energy Outlook 2004–13 scenarios. The looming supply gaps will lead to serious distortions in the world economy. “Peak Oil” represents a structural interruption. The search for sustainable structures in energy supply can no longer be put off; there is indeed already concern that there is not enough time remaining to organize a smooth transition to a post-fossil world.

For the last few years, *nonconventional* sources of oil production have been developed, namely based on the conversion of very heavy oils, such as Canadian tar sands or heavy oil in Venezuela, which, on a quantitative basis, come close to the Arabian oil reserves.

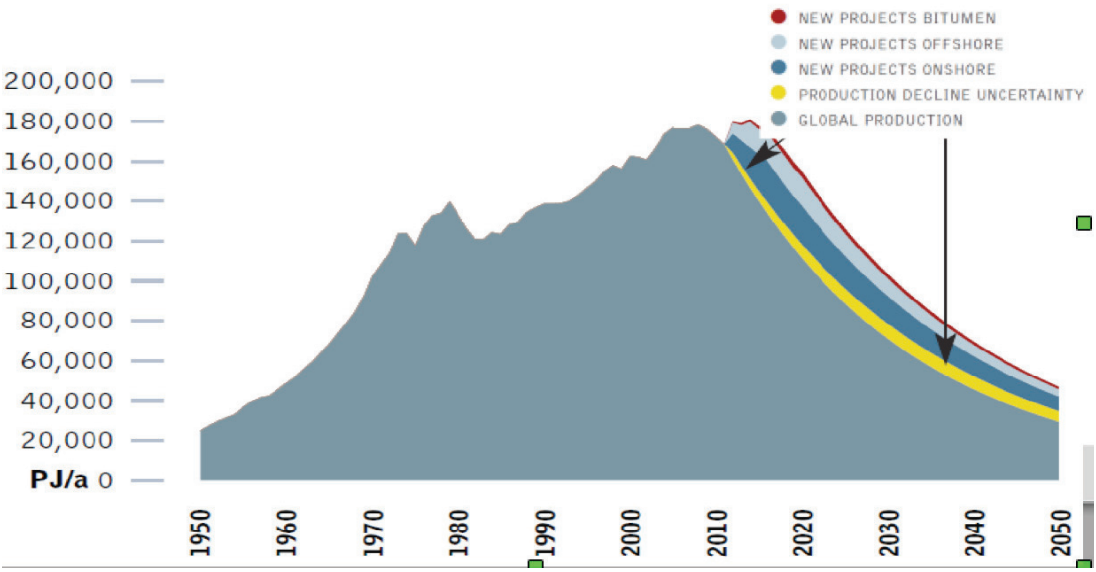

Figure 14. Global oil production 1950 to 2011 and projection to 2050 (source: Greenpeace, 2013).

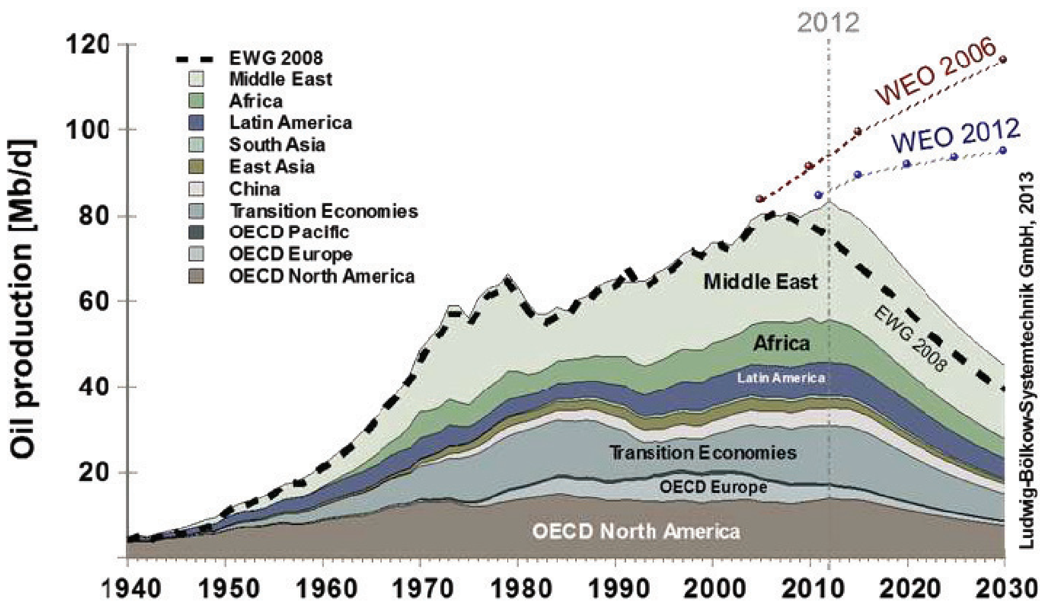

Figure 15. World oil production by regions. Dotted lines: World Energy Outlook (WEO) 2006 and 2012 forecasts (source: LBST, 2013).

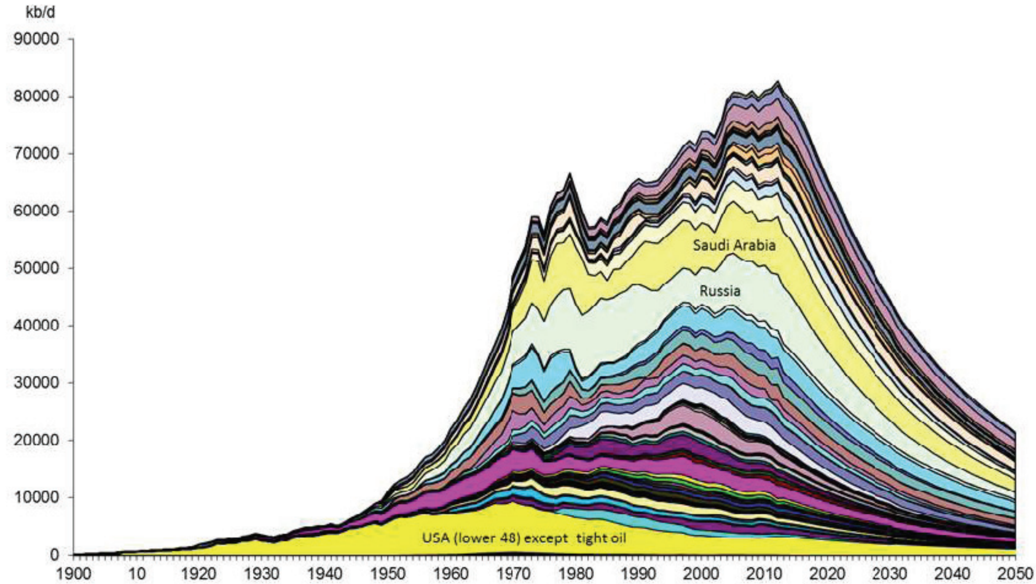

Figure 16. World oil production by country (source: LBST, 2013).

Figure 17 shows the historical and predicted development of Canadian oil production. However, it cannot be concluded from this that oil from oil sands will replace the missing conventional crude oil. The following must be considered:[6]

1. This oil is only available in the soil in very small concentrations. Utilization requires significant strip mining activities. Within the best layers the concentration is around 20%. A considerable land surface is required, which in turn requires the destruction of large areas of forest. The soil contamination resulting from extraction is immense.

2. The separation and purification of the oil uses a large amount of energy and water; the mining process is slow and is more similar to the mining process for ores than to conventional oil production. A large amount of hydrogen is required for the separation of sulfur and preparation of the oil. Natural gas is required in this process. However, only around half of the extracted bitumen is practically processable into synthetic crude oil in suitable refineries. In doing this, around 10% of the energy content of the bitumen is lost.

3. The lead times for projects are very long and the investment is high. For example, to develop a new mine with an extraction rate of 200,000 barrels/day, around 5–10 milliard USD must be invested.

4. The CO2e emissions from petrol from oil sands are comparable with those from coal.

5. The use of natural gas to process oil sands would increasingly compete with direct natural gas usage.

[6] Ludwig-Bolkow-Systemtechnik GmbH (LBST)/European Hydrogen Association, "Where Will the Energy for Hydrogen Production Come From?—Status and Alternatives", 2007. Data source: Oil, Gas, Coal–Nuclear Scenario, LBST Scenario, 2005.

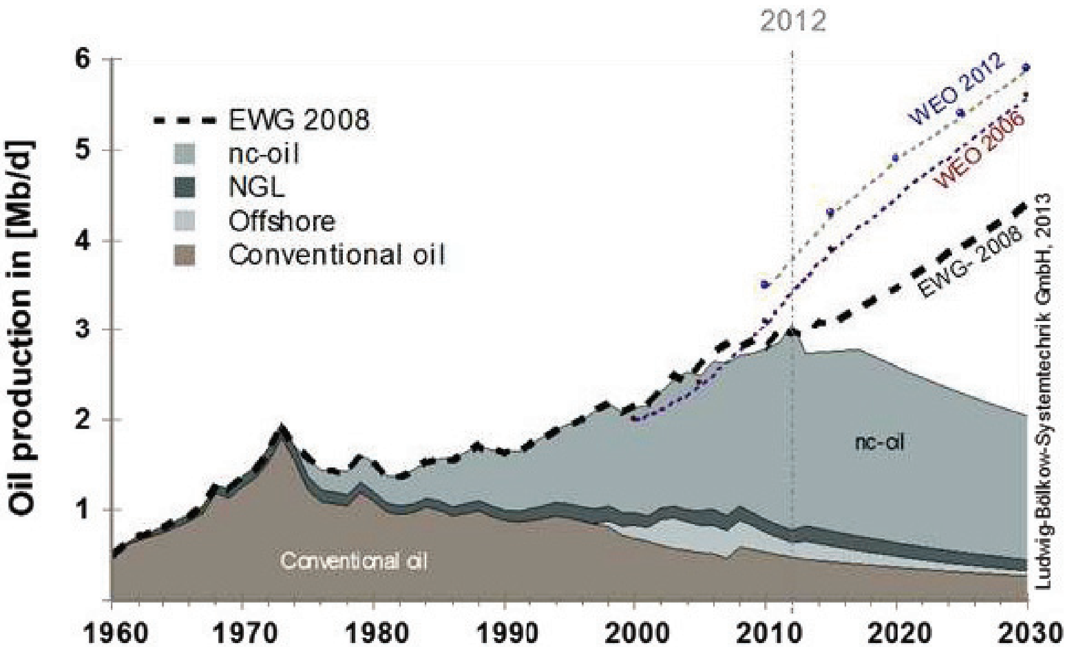

Figure 17. Conventional and nonconventional (nc) oil (tar sands) production in Canada, 1960–2030 (source: LBST, 2013).

3.2 The chaos of the reserves[6]

Public data about oil and gas reserves is strikingly inconsistent, and potentially unreliable for legal, commercial, historical and sometimes political reasons. Oil and gas companies have an interest in inflating figures, admitting later that the reserve values were not correct. Moreover, as there is no agreed definition of reserves, nor standard reporting practice, the figures may well represent different physical and conceptual magnitudes. Confusing terminology ("proven", "probable", "possible", "recoverable", "reasonable certainty"), lacking formal definitions, only adds to the problem.

Historically, private oil companies have consistently underestimated their reserves in order to comply with conservative stock exchange rules and through natural commercial caution. Whenever a discovery was made, only a portion of the geologist's estimate of recoverable resources was reported; subsequent revisions would then increase the reserves from that same oil field over time. National oil companies are mostly not subject to any sort of accountability so their reporting practices are even less clear.

Although some revision was needed after companies were nationalized, between 1985 and 1990 OPEC countries increased their declared joint reserves by 82%. Not only were these dubious revisions never corrected, but also many of these countries have reported untouched reserves for years, even if no sizeable discoveries were made and production continued at the same pace. Additionally, the former Soviet Union's oil and gas reserves have been overestimated by about 30% because the original assessments were later misinterpreted.

Whilst private companies are now becoming more realistic about the extent of their resources, the OPEC countries hold by far the majority of the reported reserves, and information on their resources is as unsatisfactory as ever. In brief, these information sources should be treated with considerable caution. To fairly estimate the world's oil resources a regional assessment of the mean backdated (i.e., "technical") discoveries would need to be undertaken. The views of the International Energy Agency (World Energy Outlook 2004) have been quite optimistic, as shown in Figure 18.

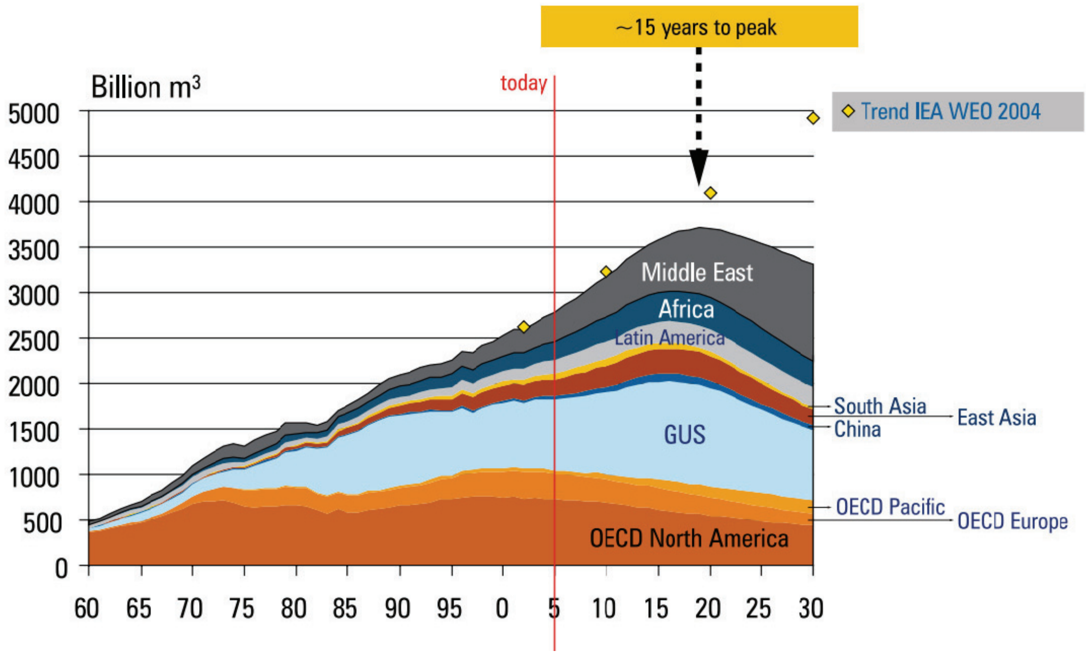

Figure 18. Oil reserves forecast up to 2030 (data: IHS Energy, BP 2005); ◊, WEO 2004 (source: LBST 2005, based on Association for the Study of Peak Oil & Gas (ASPO) scenario).

3.3 Natural gas

Natural gas has been the fastest growing fossil energy source in the last two decades, boosted by its increasing share in the electricity generation mix. Gas is generally regarded as a largely abundant resource and public concerns about depletion are limited to oil, even though few in-depth studies address the subject. Gas resources are more concentrated than oil so they were discovered faster—a few massive fields make up most of the reserves; the largest gas field in the world holds 15% of the "ultimate recoverable resources" (URR), compared to 6% in the case of the largest oil field.

Unfortunately, information about gas resources suffers from the same bad practices as oil data, because gas mostly comes from the same geological formations and the same stakeholders are involved. Most reserves are initially understated and then gradually revised upwards, giving an optimistic impression of growth. By contrast, Russia's reserves, the largest in the world, are considered to have been overestimated by about 30%, as stated above. Owing to geological similarities, gas follows the same depletion dynamics as oil, and thus the same discovery and production cycles. In fact, existing data for gas is of worse quality than for oil and some ambiguities arise as to the amount of gas already produced because flared and vented gas is not always accounted for. As opposed to published reserves, the technical ones have been almost constant since 1980 because discoveries have roughly matched production.

The scenario shown in Figure 19 assumes that world gas production can still significantly increase and will only reach its maximum in the year 2020. This is based on the assumption that the production decrease in North America and Europe will be overcompensated for by an increase in production in Russia and the Middle East (which requires significant and timely investments in these regions). However, in spite of this optimistic picture, the future of gas production is rather overshadowed by risks. A major problem lies in the overproduction and consequent depletion of several Russian fields as shown in Figure 20. A further problem for production expansion in Russia and the Middle East is the requirement to significantly expand infrastructure for the transport of liquefied natural gas. These investments require considerable resources, and time, and often also involve fighting local opposition to the construction of gasification terminals. The scenario shows the possible development based on today's estimate of reserve situations and describes an upper limit. The actual development in the coming decades could of course be adversely affected by regional bottlenecks.

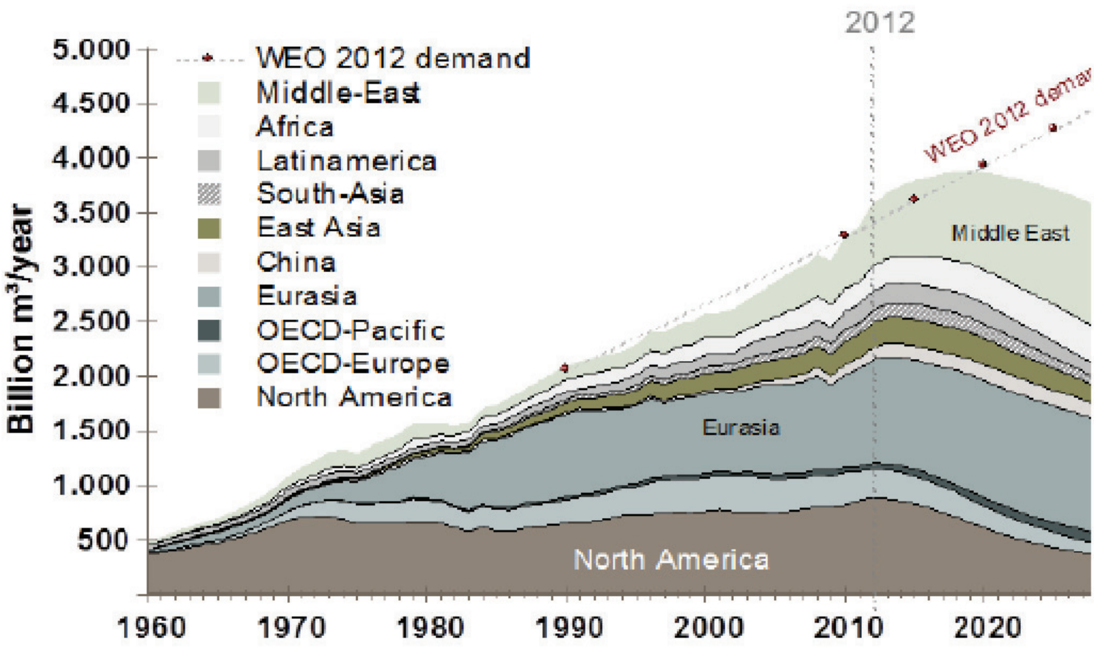

Figure 19. World gas production by region (dotted line: projection of the World Energy Organization [WEO] 2012) (source: LBST, 2013). (Note that "billion" uses the US convention, i.e. 10^9.)

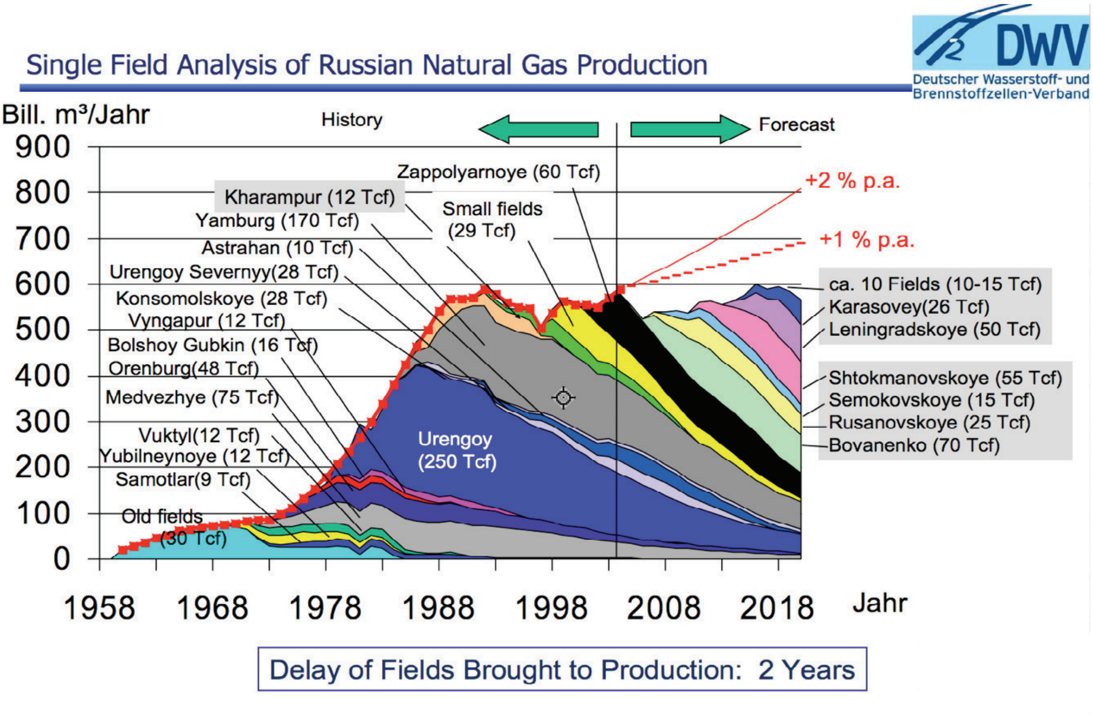

Figure 20. Single-field analysis of Russian natural gas production (source: LBST, 2006).

3.3.1 Shale gas

Shale gas is natural gas trapped within shale formations. Shale gas has become an increasingly important source of natural gas in the United States since the start of this century, and interest has spread to potential gas shales in the rest of the world.

Shale gas is produced from shales with a technology called hydraulic fracturing (fracking) to create extensive artificial fractures around well bores. Horizontal drilling is often used with shale gas wells, with lateral lengths up to 3,000 m within the shale, to create maximum borehole surface area in contact with the shale. Large quantities of high pressure water is injected, mixed with chemicals able to dissolve or otherwise structurally weaken the shale and release the gas, which is recovered from vertical wells. Figure 21 shows shale gas production schematically.

The extraction and use of shale gas can considerably affect the well environment through leaking of extraction chemicals and waste into water supplies, leading to contamination of groundwater and surface soil. Furthermore, greenhouse gases are prone to leak into the atmosphere during extraction. After the primary extraction, pollution from improper processing of the crude natural gas can be considerable. Fracking can also create local earthquakes. Several governments (France, Germany) have prohibited fracking, while elsewhere it faces strong opposition from farmers and landowners.

In 2000 shale gas provided only 1% of US natural gas production; by 2010 it was over 20% and the US government's Energy Information Administration predicts that by 2035, 46% of the United States' natural gas supply will come from shale gas.

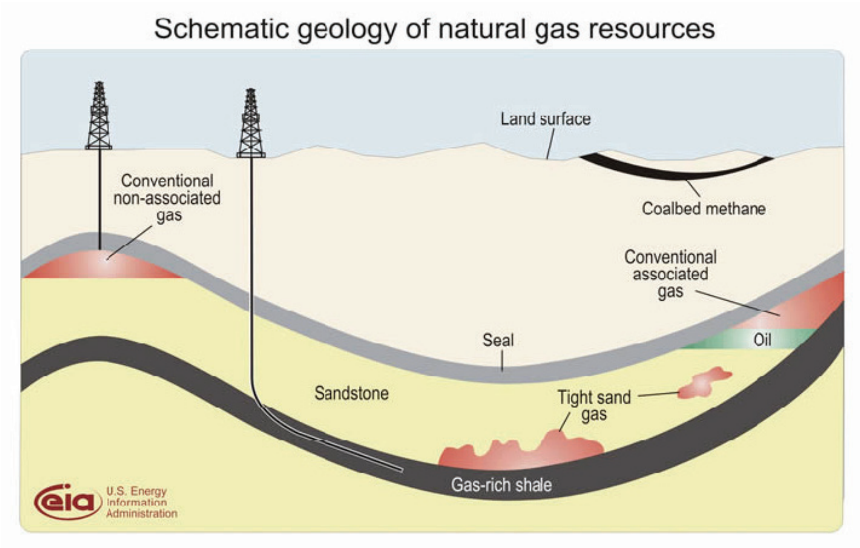

Figure 21. A schematic view of shale gas production (source: US Energy Information Administration).

Although the shale gas potential of many nations is being studied, as of 2013 only the USA Canada and China produce shale gas in commercial quantities, and only the USA and Canada have significant shale gas production. A recent report from IDDRI, the French Institute for Sustainable Development and International Relations[7] has argued that shale gas is not the resource that some governments and industry believe is the solution for the future energy needs, since:

1. Despite currently very low (and ultimately unsustainable) short-term prices of natural gas, the unconventional oil and gas revolution has had a minimal impact on the US macro-economy.

2. The unconventional oil and gas revolution has had a minimal impact on US manufacturing.

3. In the absence of further policies, the US shale gas revolution will not lead to a significant, sustained decarbonization of the US energy mix nor will it assure US energy security.

4. It is unlikely that the EU will repeat the US experience in terms of the scale of unconventional oil and gas production.

3.4 Coal

Coal was the world's largest source of primary energy until it was overtaken by oil in the 1960s. Nevertheless, coal still supplies almost one quarter of the world's energy today. Despite being the most abundant of fossil fuels, coal's development is currently threatened by environmental concerns, hence its future will unfold in the context of both energy security and global warming. Coal is abundant and more equally distributed throughout the world than oil and gas. Global recoverable reserves are the largest of all fossil fuels, and most countries have at least some. Moreover, existing and prospective big energy consumers like the USA, China, India and

---

[7] *Unconventional Wisdom: an Economic Analysis of US Shale Gas and Implications for the EU* by Thomas Spencer, Oliver Sartor and Mathilde Mathieu. IDDRI report no 05/14 (February 2014); http://www.iddri.org/Publications/Collections/Syntheses/PB0514.pdf

Australia are self-sufficient in coal and will be for the foreseeable future. Coal has been exploited on a large scale for two centuries so both the product and the available resources are well known. Unlike oil and gas, the precursor of coal was essentially deposited in a single, unique geological epoch (the Carboniferous era); no substantial new deposits are expected to be discovered. Based on the current data for worldwide coal reserves, a scenario of possible future production can be constructed. Aggregated production follows a logistic curve (adjusted to previous production and to reserves). The result is that annual worldwide coal production could be increased by 60% and would reach its maximum around 2050. In theory, the decrease in crude oil and natural gas could, therefore, partly be offset by an increase in coal usage for primary energy. In the conversion to forms of usable end energy, in particular automotive fuel, significantly higher losses are generated with coal compared with oil, so that replacement of the latter is clearly more difficult than in, for example, electricity generation or railway motive power.

Extrapolating demand forecasts, the world will consume 20% of its current reserves by 2030 and 40% by 2050. Hence, if current trends are maintained, coal would still last several hundred years. Figures 22 and 23 show the historical development of production and estimated reserves of hard coal and lignite.

It is important to note that the CO2e emissions of hard coal and, especially, lignite are significantly higher than those of crude oil and natural gas. Average values are: hard coal: 346 g CO2e/kWh, lignite: 414 g CO2e/kWh, natural gas: 203 g CO2e/kWh, petrol/diesel: 264 g CO2e/kWh.

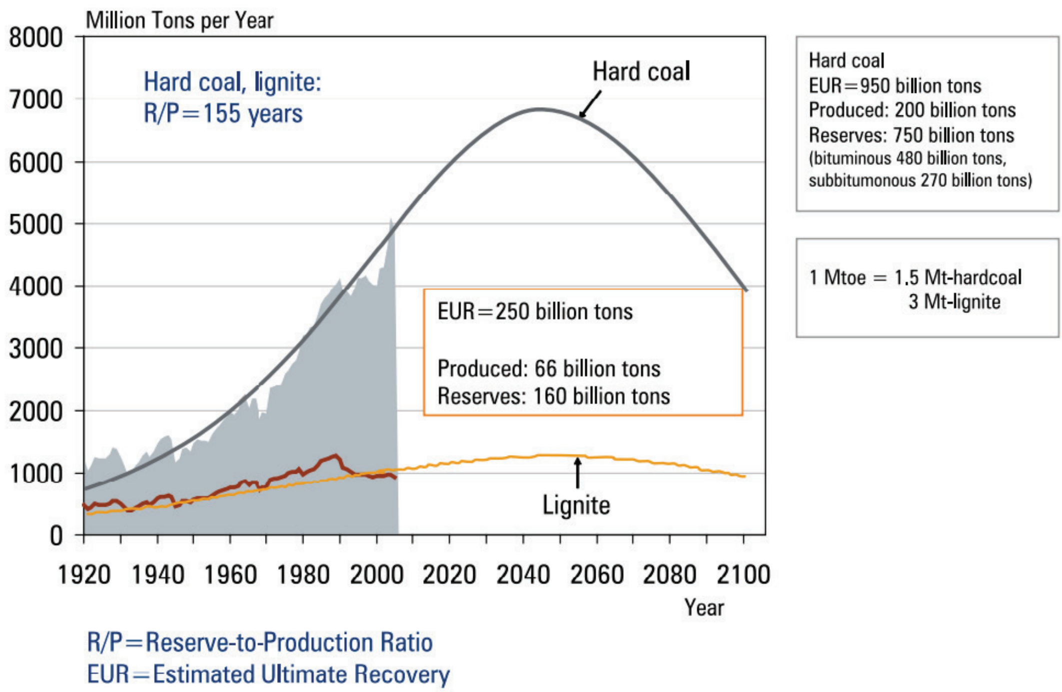

Figure 22. Historical development of coal production and reserves (source: LBST).

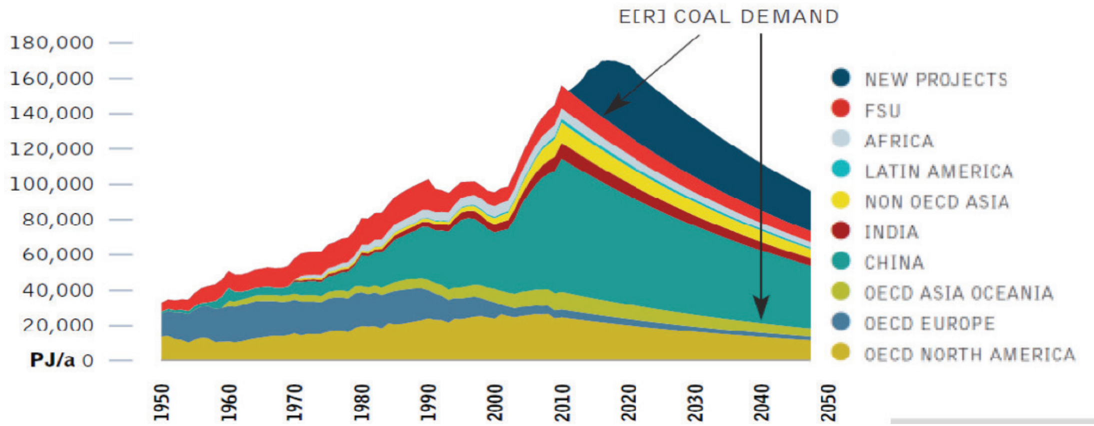

Figure 23. Coal scenario by region: base decline 2.5% per year and new projects (source: Greenpeace, 2013).

4. Carbon dioxide capture and storage and clean coal technologies

Carbon dioxide capture and storage (CCS) technology offers the possibility for significantly reducing the amount of CO2e from the combustion of fossil fuels. It is applicable to all fossil fuels but is especially relevant to coal. Some technologies process the fossil fuel before it is burned; others treat the gas after combustion in order to improve the environmental performance of conventional coal combustion. Attempting to collect the waste gases after the combustion process and storing them in geological formations is a major challenge. Precombustion processes include coal cleaning (to reduce the ash content, thereby increasing combustion efficiency) and various "bolt-on" ("end-of-pipe") technologies to reduce emissions of particulates, sulphur dioxide and nitrogen oxide, the main pollutants resulting from coal firing apart from carbon dioxide. Flue gas desulfurization, for example, most commonly involves scrubbing the flue gases using an alkaline sorbent slurry, which is typically lime- or limestone-based. More fundamental changes have been made to the way coal is burned to both improve its efficiency and further reduce emissions of pollutants. These technologies are included in the category of so-called "clean coal technology" (CCT):

- Integrated gasification combined cycle (IGCC): coal is not burnt directly but reacted with oxygen and steam to form a "syngas" (synthetic gas) composed mainly of hydrogen and carbon monoxide, which is cleaned and then burned in a gas turbine to generate electricity and produce steam to drive a steam turbine. IGCC improves the efficiency of coal combustion from 38–40% up to 50%.
- Supercritical and ultrasupercritical: these power plants operate at higher temperatures than conventional combustion, again increasing efficiency towards 50%.
- Fluidized bed combustion: comminuted coal is burned in a reactor comprising a bed of coal particles through which gas is fed to keep the fuel in an agitated state. This improves combustion, heat transfer and recovery of waste products. By raising pressures within the bed, a high pressure gas output stream can be used to drive a gas turbine, generating electricity. Emissions of both sulfur dioxide and nitrogen oxide can be reduced substantially.

- Pressurized pulverized coal combustion: This is based on the combustion of a finely ground cloud of coal particles creating high pressure, high temperature steam for power generation. The hot flue gases are used to generate electricity in a similar way to the combined cycle system.

Other potential future technologies involve the increased use of coal gasification. Underground coal gasification, for example, involves converting deep underground unworked coal into a combustible gas that can be used for industrial heating, power generation or the manufacture of hydrogen, synthetic natural gas or other chemicals. The gas can be processed to remove CO2e before it is passed on to end-users.

Storage of carbon dioxide in geological repositories such as depleted oil or gas reservoirs, aquifers and coal beds is today considered as the ultimate solution for the "final" disposal of greenhouse gases. Some tests are presently taking place in Germany and in a depleted oil field beneath the North Sea but, like other potential geological reservoirs, they are located at a great distance from the power plants. Moreover, geological instabilities and leakage rates still need to be explored and monitored during and after reposition. Storage of carbon dioxide in the deep ocean is another option but it has potentially high environmental impacts like deep sea acidification, which could greatly affect the ecosystem.

Research is underway to transform CO2e by means of metal nanoparticles, which would chemically react with the CO2e. However the process is far from being proven. As of today all the above technologies have not provided an economic model to transform produced CO2e. Employing CO2e capture and storage will increase the price of electricity from fossil fuels. Although the costs of storage depends on several factors, including the technology used for separation, transport and the kind of storage installation, experts from the IPCC calculate the additional costs at between 3.5 and 5.0 cents/kWh of power generated. This means the technology would more than double the cost of electricity today. As with nuclear waste, however, the question is whether this will just displace the problem elsewhere.

5. Uranium resources and nuclear energy

Nuclear power exploits the energy released by nuclear fission of the natural radionuclide ^{238}U. Uranium ores extracted in open pit or underground mines, typically containing about 20% uranium oxides, are refined to produce "yellow cake", which contains on average 90% "U3O8", containing a mixture of isotopes, but predominantly (99.275%) ^{238}U. The material is then enriched to a content of about 3% ^{235}U, the natural concentration of which is only a few parts per million. The distribution of ore is almost as concentrated as oil and, also similarly, does not match regional consumption. Five countries—Canada, Australia, Kazakhstan, Russia and Niger—control three quarters of the world's supply. As Russia is a significant user of uranium, however, its reserves will be exhausted within ten years. Secondary sources, such as old deposits, currently make up nearly half of worldwide uranium reserves. However, these sources will soon be used up. Mining capacities will have to be nearly doubled in the next few years to meet current needs as shown in Figure 24.

The worldwide supply of nuclear fuel that can be extracted for less than 130 USD per kilogram of uranium is guaranteed for less than the next 70 years, assuming a yearly consumption of about 66,500 tons of uranium (Figure 25). In 2005, 41,870 tons of natural uranium were mined, which met 63% of the world supply. At the moment, and probably also for the next two decades, the shortfall is covered by stocks of energy supply companies, reprocessed nuclear waste and the decommissioning of highly enriched uranium from US and Russian weapons.

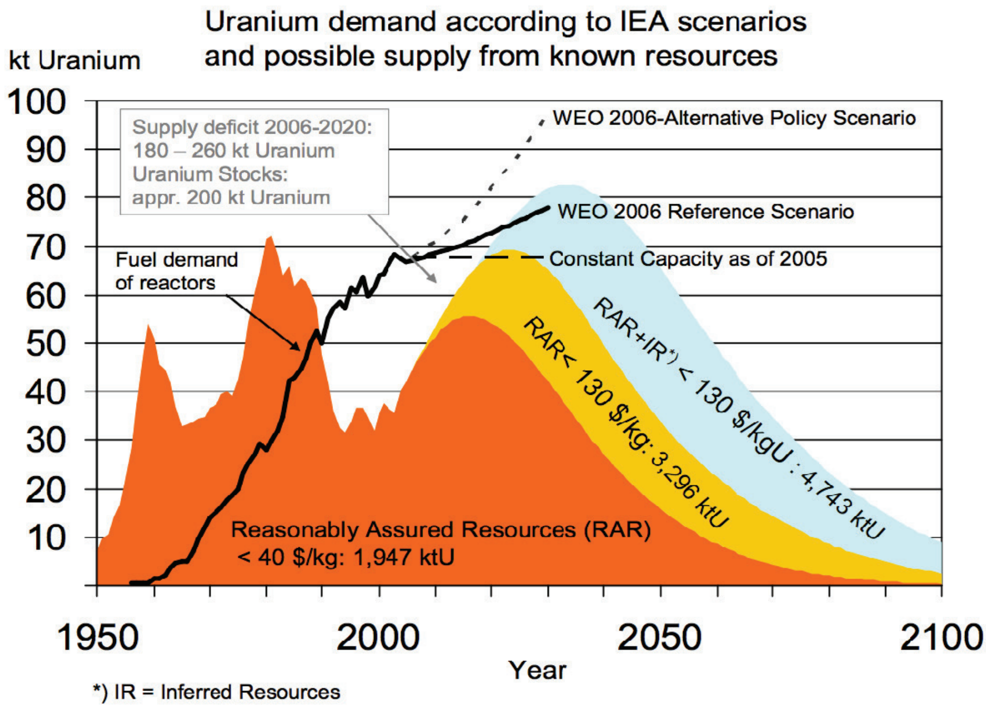

Figure 24. Uranium demand and sources according to diverse scenarios (source: LBST, 2006).

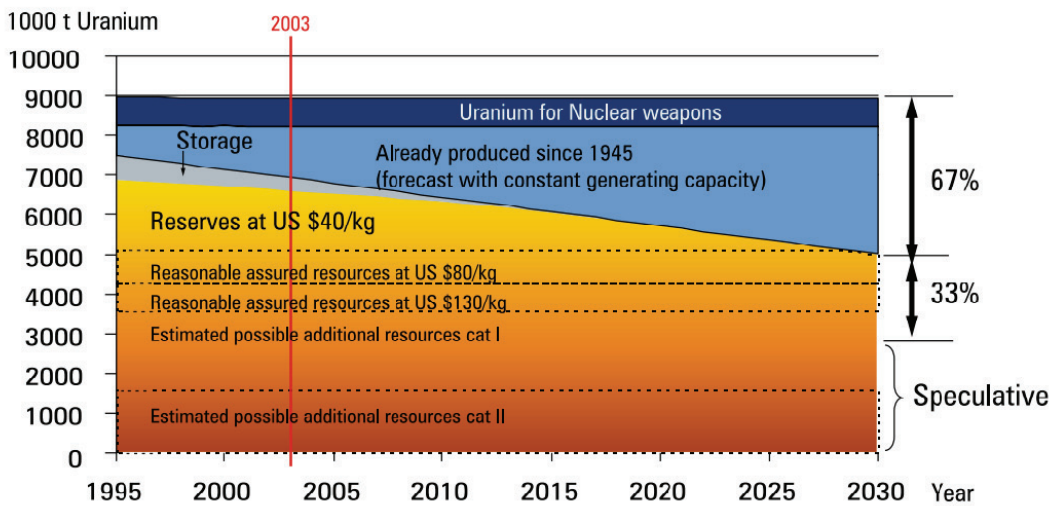

Figure 25. Uranium resources and consumption 2000–30 (sources: NEA; LBST (2006); BGR (2003)).

The sustainable development of nuclear power is presently undermined by high plant capital cost, government subsidies, the increasingly onerous safeguarding procedures, the extremely long period of construction, local opposition and, above all, by the difficulties of converting, depositing and storing nuclear waste. The amount of energy required to develop a mine, to process, to convert and to enrich the uranium, as well as to build the power plant itself is extremely high and the impact on the environment considerable, thus making nuclear power's claim of being environmentally friendly disingenuous.

Currently, 435 nuclear power plants are in operation worldwide (Figure 26). They produce 6.5% of the world's energy and generate 15.7% of the world's electricity. It should be noted that the energy efficiency of current reactor technologies is no more than 33%, thus making electricity production highly inefficient. Wasted heat is rejected at sea, in rivers or in the air by cooling towers. The age structure of the 435 civil nuclear reactors operating worldwide today essentially determines the future role of nuclear energy. The average reactor lifespan has been generally determined at the design stage to be 40 years due to loss of integrity of irradiated components. By the year 2030, 75% of the reactors installed today must be disconnected from the grid. If the number of reactors is to remain constant, 14 reactors must be built and put into operation each year throughout this interval. Worldwide, however, only around 28 reactors are under construction, and these could start operating in the next 5 to 7 years. Eleven of these reactors have been "under construction" for more than 20 years, at an outrageous cost. Moreover, several countries have decided not to build nuclear plants at all and others have decided to gradually phase out their existing ones. Under these circumstances, it is not possible to talk of a renaissance in nuclear energy.

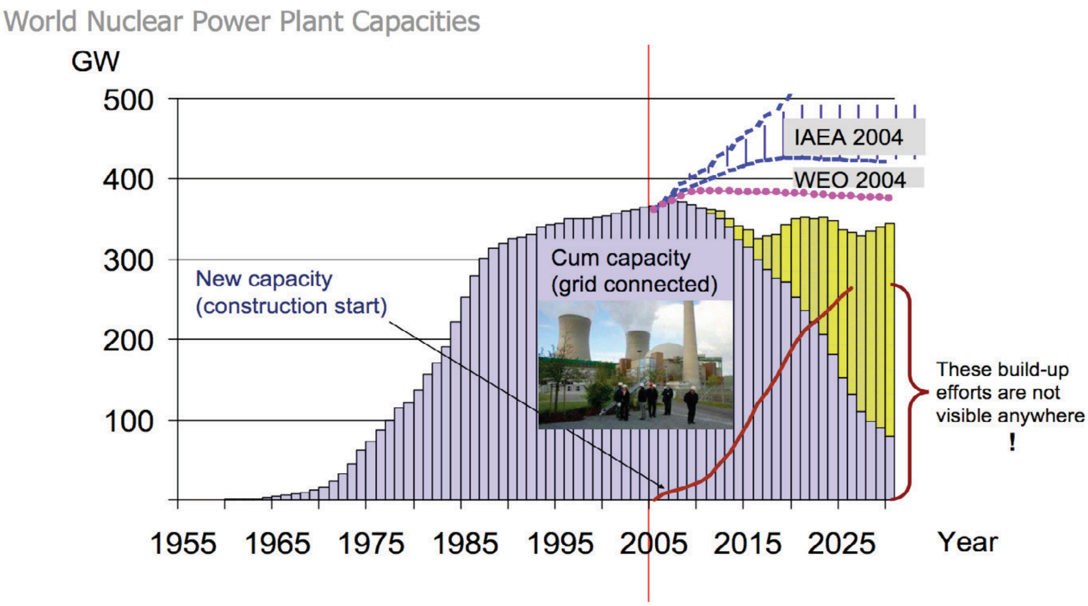

Figure 26. World nuclear power plant cumulative capacities (data source: IAEA, June 2005; scenario: LBST, 2005).

5.1 Nuclear waste storage

One of the major problems concerning nuclear energy is engendered by the storage of nuclear waste. Several countries store in a provisional fashion the spent fuel and the plants' nuclear waste. Others, like France, reprocess most of the waste, extracting plutonium and other materials that are then reutilized as new fuel. Final storage is another unresolved issue. There is not a single final storage facility for highly radioactive nuclear waste available anywhere in the world. Safe secure storage of high level waste over thousands of years remains unproven, leaving a deadly legacy for future generations. Despite this, the nuclear industry continues to generate more and more waste each day.

6. Contribution of all fossil and nuclear fuels[4, 5]

A scenario of the future availability of fossil and nuclear energy resources is shown in Figure 27. On the basis of what we know today, a strong decline in oil production after "peak oil" is highly probable. The reason lies in the oil production technologies used today, which aim to exhaust the fields as quickly as possible. Hence, after peak production has been reached, a quick drop in production rates will be experienced. To offset this, new areas of production, such as within the Arctic Circle, are being explored, notwithstanding strong opposition from diverse sources.

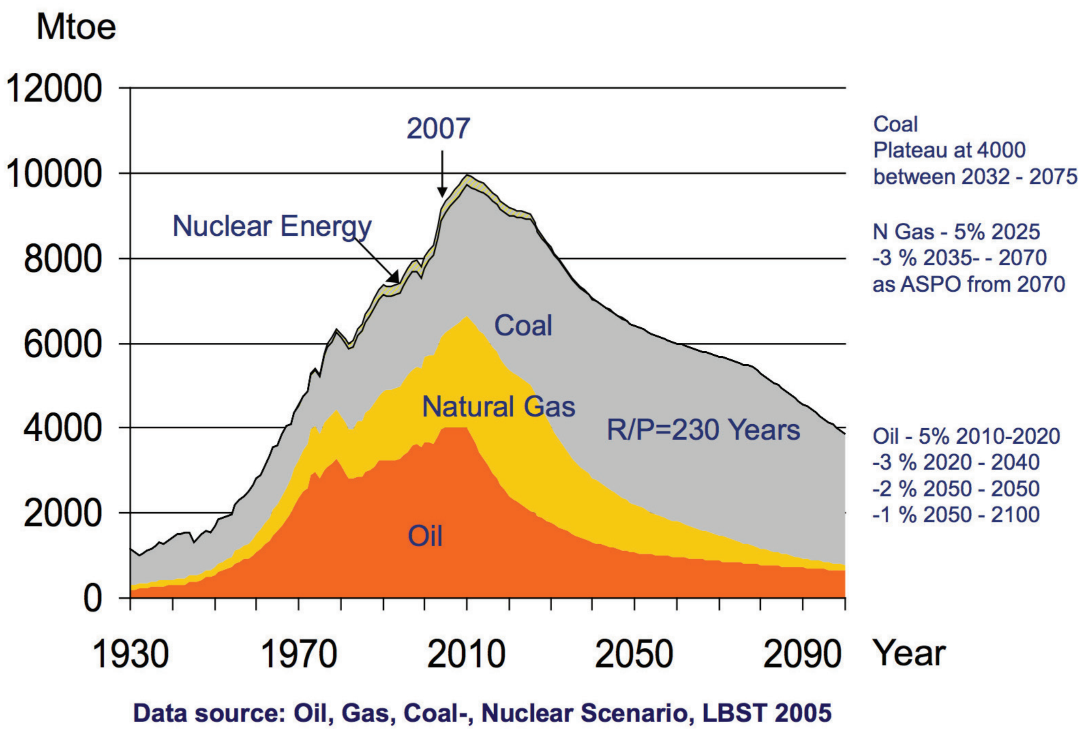

Figure 27. Reserves of fossil and nuclear fuels to 2090 (source: LBST, 2005).

Industry is trying to develop nonconventional oil resources such as tar sands in Canada as well as shale gas at the enormous cost to the environment. These modes of production are not sustainable and, independently from strong and growing local opposition on grounds of environmental damage and loss of amenity, will probably be discontinued. Achieving peak production for oil, and subsequently for natural gas, will therefore shortly thereafter leave a noticeable gap in world energy supply, which cannot be filled by other fossil primary energy sources. Coal reserves known to us today, with a range of coverage of around 160 years, will indeed permit increasing production until around 2050, but in assessing coal one should take into account that the data quality is poorer than for crude oil (for example, since 1992 China has been reporting exactly the same reserve figures each year, but in this period around 20% of the "proven" reserves have already been used up). China currently produces the largest amount of coal worldwide (almost double that of the USA). However, China's reserves are only half those of the USA. For Canada too, another major source, almost exactly the same reserve figures are published today as in 1986.

In the light of the strong lobby of the oil, coal and gas companies and support by the WEO who maintain the assurance that fossil fuels will still be available in useful quantities in the future, it is necessary to provide four realistic statements about reserves:

- Fossil energies are increasingly difficult to exploit and, therefore, are becoming more expensive;
- Environmental considerations will put increasing pressure on the burning of coal, oil and gas;
- Renewable energies have shown an average growth rate of far more than 15% per year over the past 15 years, and have become increasingly cost-efficient; the price gap between conventional and unconventional energy supplies is becoming ever smaller;
- The levelized cost of electricity (LCOE) is declining for wind, solar photovoltaics (PV), concentrated solar power (CSP) and some biomass technologies. While hydropower and geothermal electricity produced at good sites are still the cheapest ways to generate electricity, the rapid growth in the deployment of solar and wind is driving a convergence in electricity generation costs for renewable power generation technologies at low levels.[8]

7. What is the solution for "saving the planet"?

The inexorable decrease of fossil fuel resources is an incontrovertible reality. Alongside that, there is evidence that global warming is caused by human activity. Nevertheless, it is apparently ignored by the US Administration, which refuses to ratify the Kyoto Protocol;[9] Canada has withdrawn. Perhaps not surprisingly, the oil and gas industries tend to ignore the effects of GHG emissions. The IPCC seeks to demonstrate beyond any doubt the anthropogenic origin of global warming and has strongly suggested urgent mitigation via a strong reduction of emissions in all countries.

---

[8] Renewable Power Generation Costs 2012. International Renewable Energy Agency (IRENA).

[9] Fracking might make the USA self-sufficient in energy within 10 years and, hence, even less likely to ratify the Kyoto Protocol.

7.1 The global Energy (R)evolution scenario[5]

The Energy (R)evolution scenario has became a well known and well respected energy analysis since it was first published for Europe in 2005. The fourth Global Energy (R)evolution (2012), whose update is a basic ingredient for this review, follows the scenarios published in 2007, 2008 and 2010. The IPCC's Special Report on Renewable Energy and Climate Change (SRREN 2010) chose the Energy (R)evolution 2010 scenario as one of four benchmarks for climate change mitigation. The Energy (R)evolution 2012 provides a consistent fundamental pathway for how to protect our climate: getting the world from where we are now to where we need to be by phasing out fossil fuels and cutting CO2e emissions while ensuring energy security; it takes into account the significant changes in the global energy sector debate over the past two years.

In Japan, the Fukushima nuclear disaster following the devastating tsunami on 11 March 2011 accelerated the phase-out of nuclear power in German and Switzerland and raised the level of debate in many other countries. The Deepwater Horizon disaster in the Gulf of Mexico in 2010 highlighted the damage that can be done to ecosystems and livelihoods by oil extraction activity; nevertheless oil companies have started new oil exploration in ever more sensitive environments such as within the Arctic Circle.

In the analysis described by the Energy (R)evolution report, and used in this paper, two different scenarios characterize the wide range of possible paths for the future energy supply system: (i) the Reference scenario, reflecting a continuation of current trends and policies ("business as usual" or BAU); and (ii) the global Energy (R)evolution scenario, which is designed to achieve a set of dedicated environmental policy targets.

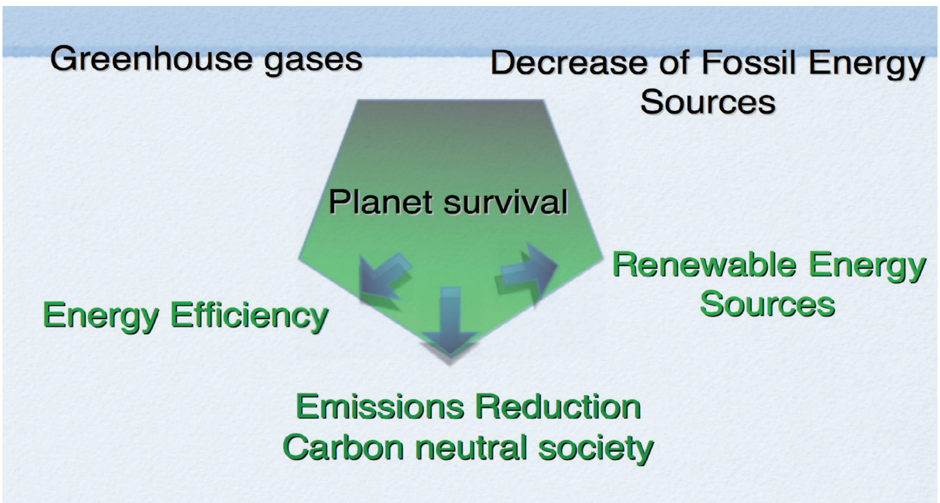

Figure 28. The global Energy (R)evolution (source: EREC–Greenpeace).

The Reference scenario is based on that published by the International Energy Agency in the World Energy Outlook (WEO) 2004 and updated in 2013. This takes into account only existing policies. The assumptions include, for example, continuing exploration and production of fossil fuels including exploitation of tar sands and shale gas and investing in carbon capture and storage (CCS). The Reference scenario does not include extended policies to reduce greenhouse gas emissions. As the IEA's scenario only covers a time horizon up to 2035 it has been extended here by extrapolating its key macroeconomic indicators. This provides a baseline for comparison with the Energy (R)evolution scenario.

The five key principles behind the Energy (R)evolution are:

- To implement renewable solutions, especially through decentralized energy systems and (slightly contradictorily) grid expansion;
- To respect the natural limits of the environment;
- To phase out dirty, unsustainable energy sources;
- To create greater equity in the use of resources;
- To decouple economic growth from the consumption of fossil fuels.

These principles should be implemented by the following objectives:

1. Curbing global energy demand. The world's energy demand is projected by combining population development, GDP growth and energy intensity. Under the Reference scenario, total primary energy demand increases by 61% from about 500 EJ (exajoules) per annum in 2009 to 806 EJ per annum in 2050. In the Energy (R)evolution scenario, demand increases by only 10% compared to current consumption until 2020 and decreases slightly afterwards back to 2009 levels.

2. Controlling global power demand. Under the Energy (R)evolution scenario, electricity demand is expected to increase unevenly, the main growth being in households and services. With adequate efficiency measures, however, a higher increase can be avoided, leading to electricity demand of around 41,000 TWh/year in 2050. Compared to the Reference scenario, efficiency measures avoid the generation of 12,800 TWh/year.

3. Reducing global heating demand. Potential efficiency gains in the heat supply sector are even larger than in the electricity sector. Under the Energy (R)evolution scenario, final demand for heat supply can eventually be reduced significantly. Compared to the Reference scenario, consumption equivalent to 46,500 PJ/year is avoided through efficiency measures by 2050. The lower demand can be achieved by energy-related renovation of the existing stock of residential buildings and the introduction of low energy standards; and by "energy-plus-houses" for new buildings so people can enjoy the same comfort and energy services as they are used to at present, but sustainably.

4. Development of global industrial energy demand. Energy demand in the industry sector will grow in both scenarios. While the economic growth rates in the Reference and the Energy (R)evolution scenarios are identical, the growth of overall energy demand is different due to a faster increase of the energy intensity in the alternative case. Decoupling economic growth from energy demand is key to reach a sustainable energy supply by 2050; the Energy (R)evolution scenario envisages using 40% less energy per unit of GDP than the Reference case.

5. Electricity generation. A dynamically growing renewable energy market will compensate for phasing out nuclear energy and commissioning fewer fossil fuel-fired power plants. By 2050, 94% of the electricity produced worldwide should come from renewable energy sources. "New" renewables—mainly wind, PV and geothermal energy—will contribute 60% of electricity generation. The Energy (R)evolution scenario projects an immediate market development with high annual growth rates already achieving a renewable electricity share of 37% by 2020 and 61% by 2030. The installed capacity of renewables should reach almost 7,400 GW in 2030 and 15,100 GW by 2050 (Figure 29).

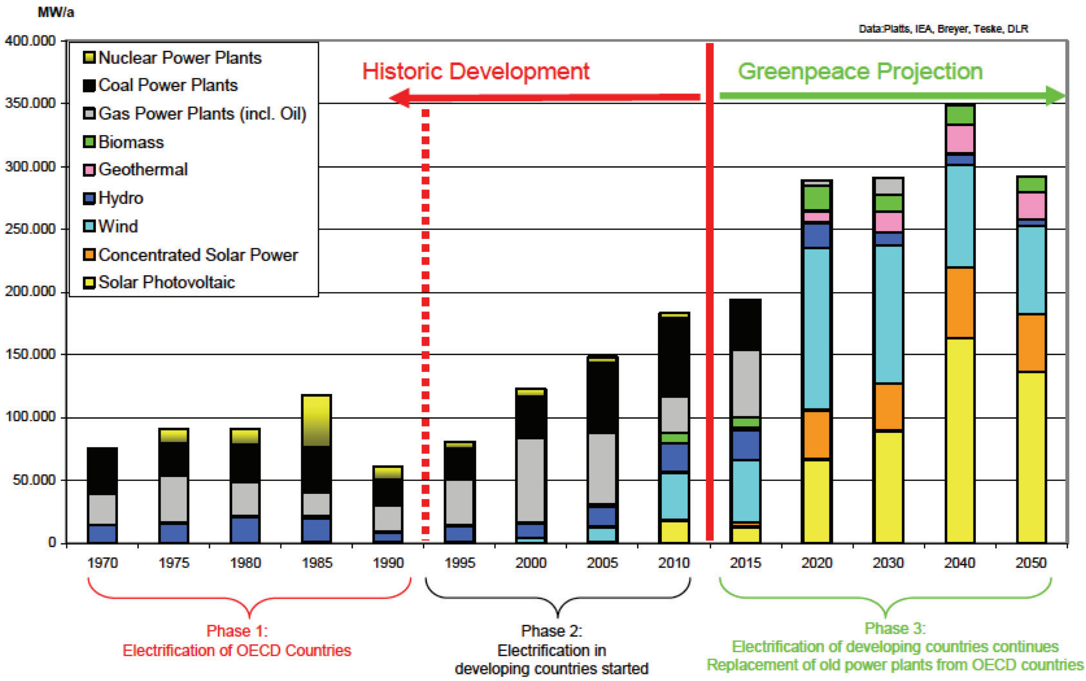

Figure 29. Global annual power plant market—the past 40 years and a projection of the next 40 years (sources: Teske, Platts, IEA, Breyer, DLR).

6. Future costs of electricity generation. Under the Energy (R)evolution scenario the cost of electricity generation increases slightly compared to the Reference scenario. This difference will be on average less than 0.0035 €/kWh up to 2020. However, if fossil fuel prices go higher than the model assumes, this gap will decrease. Electricity generation costs will become economically favourable under the Energy (R)evolution scenario by 2025 and by 2050 costs will be significantly lower: about 0.06 €/kWh, or 45% below those in the Reference version (Figure 30).

7. The future electricity bill. Under the Reference scenario, the unchecked growth in demand results in total electricity supply costs rising from today's €1,650 milliards per year to more than €6,200 milliards in 2050. The Energy (R)evolution scenario helps to stabilize energy costs: increasing energy efficiency and shifting to renewable energy supply means long term costs for electricity supply are 22% lower in 2050 than in the Reference scenario (including estimated costs for implementing efficiency measures).

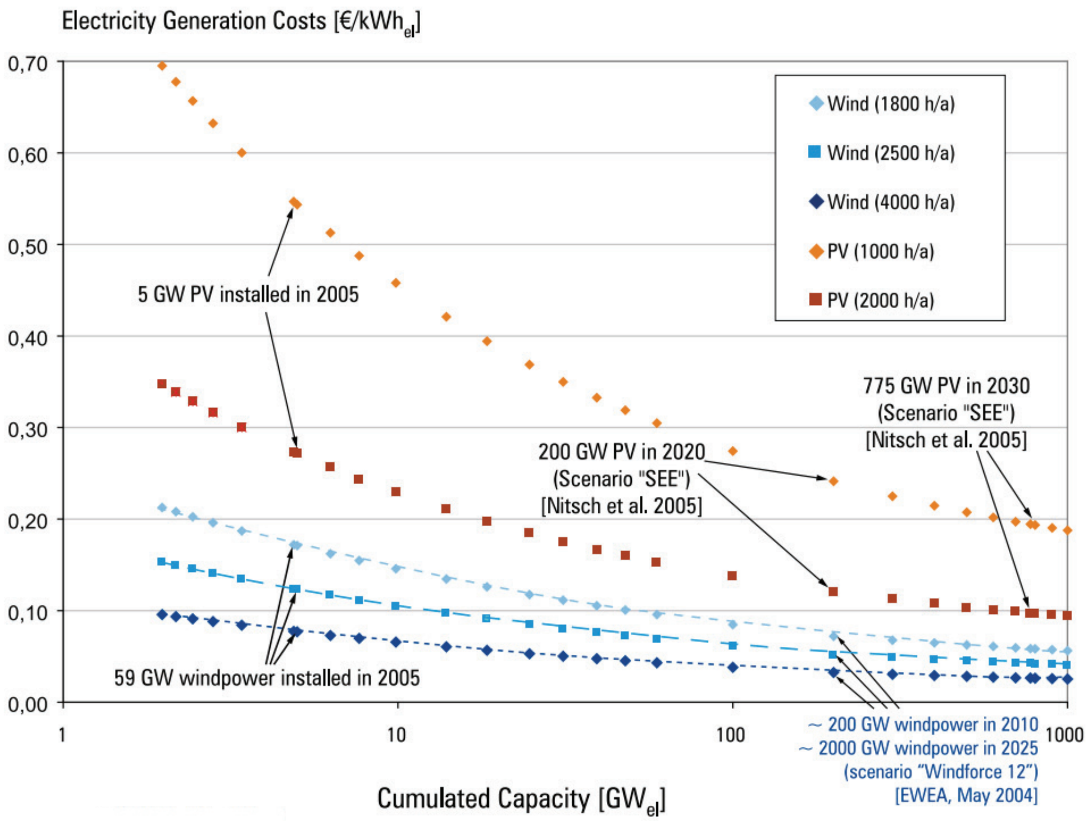

Figure 30. Renewable electricity generation costs trend (data source: EWEA, May 2004; data compilation and graphics: LBST).

8. Future investment in power generation. The overall global level of investment required in new power plants up to 2020 will be in the region of €8 × 10^{12} in the Reference case and €14.1 × 10^{12} in the Energy (R)evolution. The need to replace the aging fleet of power plants in OECD countries and install new power plants in developing countries will be the major investment drivers. Depending on the local resources, renewable energy sources (for example wind in a windy area) can produce electricity at the same cost levels as coal or gas power plants. Solar photovoltaic electricity is already approaching grid parity in some industrialized countries. For the Energy (R)evolution scenario to become reality before 2050 would require about €35.3 × 10^{12} of investment in the power sector (including investments for replacement after the economic lifetime of the plants). Under the Reference scenario, total investment would be split 48% to 52% between conventional power plants and renewable energy plus cogeneration (combined heat and power—CHP) up to 2050. Under the Energy (R)evolution scenario 95% of global investment would be in renewables and cogeneration. Up to 2030, the power sector investment that does go to fossil fuels would be focused mainly in cogeneration plants. The average annual investment in the power sector under the Energy (R)evolution scenario from today to 2050 would be €880 × 10^9, compared to €388 × 10^9 in the Reference case.

9. Fuel costs savings. Because renewable energy, except biomass, has no fuel costs, the fuel cost savings in the Energy (R)evolution scenario reach a total of €52.8×10^{12} up to 2050, or €950×10^{9} per year. The total fuel cost savings therefore would cover more than two times the total additional investments compared to the Reference scenario. These renewable energy sources would then go on to produce electricity without any further fuel costs beyond 2050, while the costs for coal and gas will continue to be a burden on national economies.

10. Heating supply. Renewables currently provide 25% of the global energy demand for heat supply, the main contribution coming from biomass. In the Energy (R)evolution scenario, renewables provide more than 50% of the world's total heat demand in 2030 and more than 90% in 2050. Energy efficiency measures can decrease the current demand for heat supply by 10 %, and still support improving living standards for a growing population.

11. Future investments in the heat sector. The heat sector in the Energy (R)evolution scenario would require a major revision of current investment strategies in heating technologies. In particular, enormous increases in installations are required to realize the potential of the not-yet-common solar and geothermal technologies and heat pumps. Installed capacity needs to increase by a factor of 60 for solar thermal and by a factor of over 3,000 for geothermal and heat pumps. Because the level of technological complexity in this sector is extremely variable, the Energy (R)evolution scenario can only be roughly calculated, to require around €19.5×10^{12} investment in renewable heating technologies up to 2050. This includes investments for replacement after the economic lifetime of the plant and is approximately €480×10^{9} per year. For example, in France more than 40% of household heating is supplied by electricity. Conversion of old buildings to the new technologies will be extremely costly in many cases.

12. Future employment in the energy sector. The Energy (R)evolution scenario results in more global energy sector jobs at every stage of the projection. There are 23.3 million energy sector jobs in the Energy (R)evolution in 2015, and 18.7 million in the Reference scenario. In 2020, there are 22.6 million jobs in the Energy (R)evolution scenario, and 17.8 million in the Reference scenario. In 2030, there are 18.3 million jobs in the Energy (R)evolution scenario and 15.7 million in the Reference scenario.

There is a decline in overall job numbers under both scenarios between 2010 and 2030. Jobs in the coal sector decline significantly in both scenarios, leading to a drop of 6.8 million energy jobs in the Reference scenario by 2030. Strong growth in the renewable sector leads to an increase of 4% in total energy sector jobs in the Energy (R)evolution scenario by 2015. Job numbers fall after 2020, so jobs in the Energy (R)evolution are 19% below 2010 levels in 2030. However, this is 2.5 million more jobs than in the Reference scenario. Renewable energy accounts for 65% of energy jobs by 2030, with the majority spread over wind, solar PV, solar heating and biomass.

13. Global transport. In the transport sector it is assumed that energy consumption will continue to increase under the Energy (R)evolution scenario up to 2020 due to fast-growing demand for services. After that, it falls back to the level of current demand by 2050. Compared to the Reference scenario, transport energy demand is reduced overall by 60%, or about 90,000 PJ/year by 2050. Energy demand for transport under the Energy (R)evolution scenario will therefore increase between 2009 and 2050 by only 26% to about 60,500 PJ/year. Significant savings are made from a shift towards smaller cars, triggered by economic incentives, together with a significant shift in propulsion technology towards electrified railway trains, along with reducing vehicle kilometres travelled per year. In 2030, electricity will provide 12% of the transport sector's total energy demand in the Energy (R)evolution, while in 2050 the share will be 44%. With a share of 33% of CO2e emissions in 2050, this sector will be the main source of emissions, ahead of industry and power generation.

14. Primary energy consumption. Under the Energy (R)evolution scenario the overall primary energy demand will be reduced by 40% in 2050 compared to the Reference scenario (Figure 31). In this projection almost the entire global electricity supply, including the majority of the energy used in buildings and industry, would come from renewable energy sources. The transport sector, in particular aviation and shipping, would be the last sector to become fossil fuel-free.

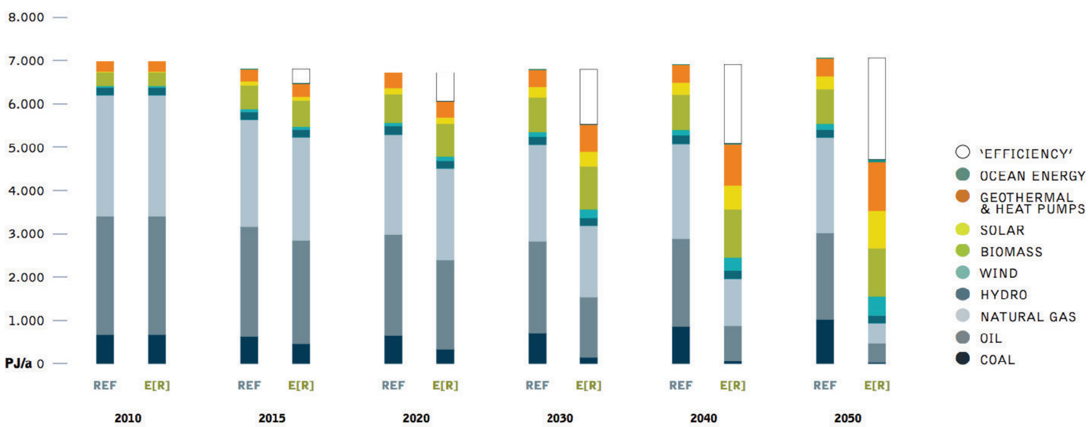

Figure 31. Primary energy consumption according to the Reference scenario and the Energy (R)evolution scenario (source: EREC–Greenpeace).

15. Evolution of carbon dioxide emissions. Worldwide CO2e emissions in the reference case will increase by 62%, while under the Energy (R)evolution scenario they will decrease from 27,925 million tons in 2009 to 10,590 million tons in 2050. Annual *per capita* emissions will drop from 4.1 tons CO2e to 2.4 tons CO2e in 2030 and 0.3 tons CO2e in 2050. Even with a phase-out of nuclear energy and increasing demand, CO2e emissions will decrease in the electricity sector. In the long term, efficiency gains and greater use of renewable electricity for vehicles will also reduce emissions in the transport sector. By 2050 global energy-related CO2e emissions are 85% of the 1990 levels (Figure 32).

To make the Energy (R)evolution real and to avoid dangerous climate change, Greenpeace, the Global Wind Energy Industry (GWEC), the European Renewable Energy Council (EREC) and the authors of the reports emanating from these organizations demand that the following policies and actions are implemented in the energy sector:

1. Phase out all subsidies for fossil fuels and nuclear energy;

2. Internalize the external (social and environmental) costs of energy production through "cap and trade" emissions commerce;

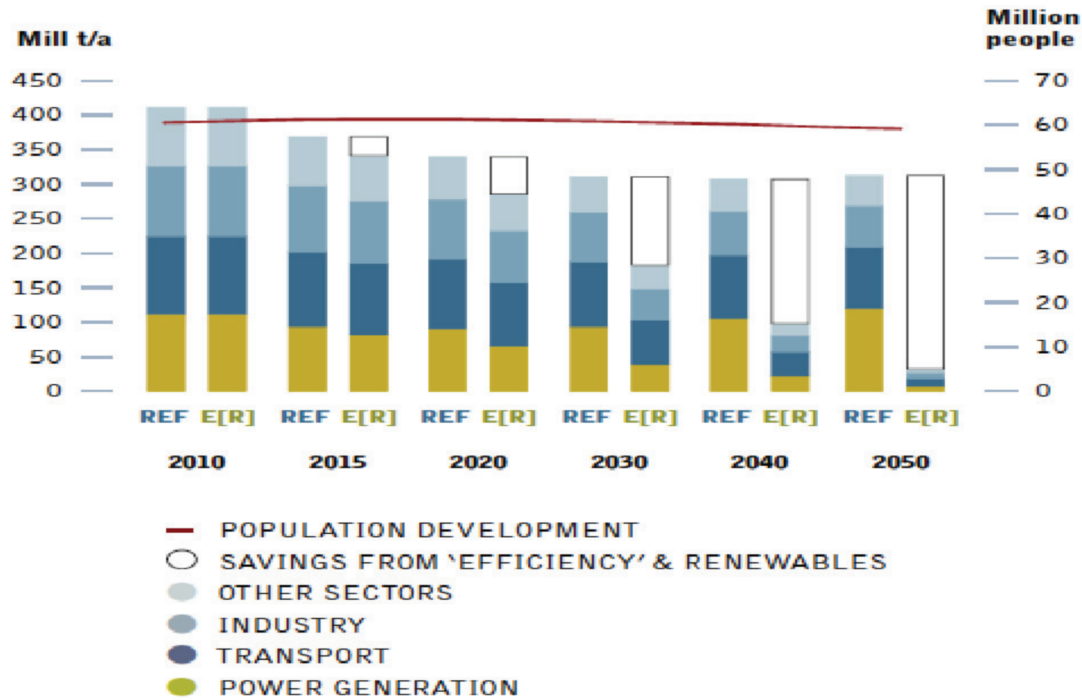

Figure 32. Development of CO2e emissions by sector under Reference scenario (REF) and under the Energy (R)evolution scenario (E[R]). (source: GWEC, EREC, Greenpeace).

3. Mandate strict efficiency standards for all energy-consuming appliances, buildings and vehicles;

4. Establish legally binding targets for renewable energy and combined heat and power generation;

5. Reform the electricity markets by guaranteeing priority access to the grid for renewable power generators;

6. Provide defined and stable returns for investors, for example by feed-in tariff programmes;

7. Implement better labelling and disclosure mechanisms to provide more environmental product information;

8. Increase research and development budgets for renewable energy and energy efficiency.

On the other hand, a significant segment of the public perceives the present subsidies for renewables as contributing to high domestic energy bills, thereby diminishing enthusiasm for developing renewable energy sources. Another segment is concerned about the loss of amenity implied by the erection of windmills and dams in areas of great natural beauty. The political problems in reconciling these diverse interests may well surpass the abilities of the average government.

8. Development of global energy demand

8.1 Energy efficiency

Energy efficiency is essential to reduce consumption: it offers a powerful and cost-effective tool for achieving a sustainable energy future. Improvements in energy efficiency can reduce the need for investment in energy infrastructure, cut fuel costs, increase competitiveness and improve consumer welfare. Environmental benefits will also be achieved by the reduction of greenhouse gas emissions and local air pollution. The most important sectors in which energy savings can be applied are industry, buildings, appliances and transport. A few examples show where energy saving can be applied. In the industrial sector approximately 65% of electricity consumption is used to drive electric motors. This can be reduced by employing variable speed drives, high efficiency motors and using efficient pumps, compressors and fans. The savings potential here is estimated at up to 40%. In some industries, the savings have already been made. It is noteworthy that the all-electrified Swiss Federal Railways use no more electricity than several decades ago, despite a great increase in the tonnage hauled, since the modern electric motors powering their new generation locomotives are far more energy efficient than the old ones. The production of primary aluminium from alumina (the main constituent of bauxite) is a very energy-intensive process. It is produced by passing a direct current through a bath with alumina dissolved in a molten cryolite electrode. On the other hand, aluminium production from recycled scrap uses only 5–10% of the energy required for primary production because it involves merely remelting the metal instead of an electrochemical reduction process. If recycling increases from 22% of aluminium production in 2005 to 60% in 2050 this would save 45% of current electricity use.

In buildings, intelligent architectural design, new materials, highly efficient insulation and passive solar design in both residential and commercial buildings will help to curb the growing demand for active air-conditioning and heating, saving up to 80% of the average energy demand.[10]

Electric heating should be banned and replaced by wood- or gas-burning boilers, radiators, heat pumps and solar collectors. For household appliances such as washing machines, dishwashers, television sets and refrigerators, energy use can typically be reduced by 30% through the use of low-consumption products and by 80% with advanced technologies, such as induction cookers. For office appliances energy use can be reduced by 50–75% through a combination of power management and energy-efficient computer systems. International energy efficiency labelling is now common in most developed countries. Use of standby mode for appliances is on average responsible for 5–13% of electricity use by households in OECD countries. Replacement of existing appliances by those with the lowest losses could reduce power consumption by 70%. "Low-consumption" light bulbs have now become compulsory in several countries despite containing toxic metals and, hence, posing a certain risk to public health.

In the transport sector, the use of hybrid (electric/combustion), hybrid/ rechargeable, full electric and future fuel cell-powered vehicles as well as other efficiency measures such as new construction materials (such as lightweight composites), aerodynamic design etc. could reduce

[10] W.J. Batty, Eco-design and sustainability. In: J.J. Ramsden, S. Aida and A. Kakabadse, *Spiritual Motivation: New Thinking for Business and Management*, pp. 130–146. Basingstoke: Palgrave (2007).

energy consumption in passenger cars by up to 80% in 2050. Reduced energy consumption will be further achieved by shifting the transport of goods from road to rail, by surtaxing road freight and by improving hub intermodal transport. Changes in mobility-related behaviour patterns will, however, be essential in effecting these reductions.

An accelerated increase in energy efficiency, which is a crucial prerequisite for renewable sources achieving a sufficiently large share of overall energy supply, will be beneficial not only for the environment but from an economic point of view. Taking into account the full life cycle, in most cases the implementation of energy efficiency measures saves money compared to increasing energy supply. A dedicated energy efficiency strategy, including improvement of legislation, labelling and monitoring, will help to compensate for the additional costs incurred during the market introduction phase of renewable energy sources. Actually, it is easy to demonstrate that the additional costs incurred in improving efficiency are offset even in the short term by energy saving. These savings are, however, likely to be dwarfed by those achievable via *cutting out extravagances* (CoE), but serious studies of the latter, including its effects and achievability, are still lacking.

Under the Energy (R)evolution scenario, electricity demand is expected to increase, with households and services the main source of growing consumption. With the implementation of efficiency measures, however, considerable reduction can be achieved, leading to an electricity demand of around 41,000 TWh/year in 2050. Compared to the Reference scenario, efficiency measures avoid the generation of 12,800 TWh/year. As a result of energy-related renovation of the existing stock of residential buildings, as well as the introduction of low-energy standards and "passive houses" for new buildings, enjoyment of the same comfort and energy services will be accompanied by a much lower future energy demand. New advanced standards such as the Swiss-developed "Minergie" are being applied in many countries and have become compulsory in some European countries.

8.2 Electricity generation

The development of the electricity supply sector is characterized by a dynamically growing renewable energy market and an increasing share of renewable electricity. This will compensate for the phasing-out of nuclear energy at the end of the life of the reactors presently in operation and reduce the number of fossil fuel-fired power plants required for grid stabilization.

The availability of the renewable energy sources on Earth is shown in Figure 33. These can provide 3,078 times current global energy needs. By 2050, 70% of the electricity produced worldwide is anticipated to come from renewable energy sources. "New" renewables—mainly wind, solar thermal energy and PV—will contribute 42% of electricity generation.

Technology advances, including new types of solar collectors and increased efficiency of materials and components,[11] new wind generators including offshore,[12] as well as other resource-transforming equipment, should considerably improve electricity and heat generation in the future.

[11] A.J. Parnell, Nanotechnology and the potential for a renewable solar future. *Nanotechnology Perceptions* **7** (2011) 180–187.
[12] But see J. Platts, The offshore wind energy nano-industry. *Nanotechnology Perceptions* **9** (2013) 91–95.

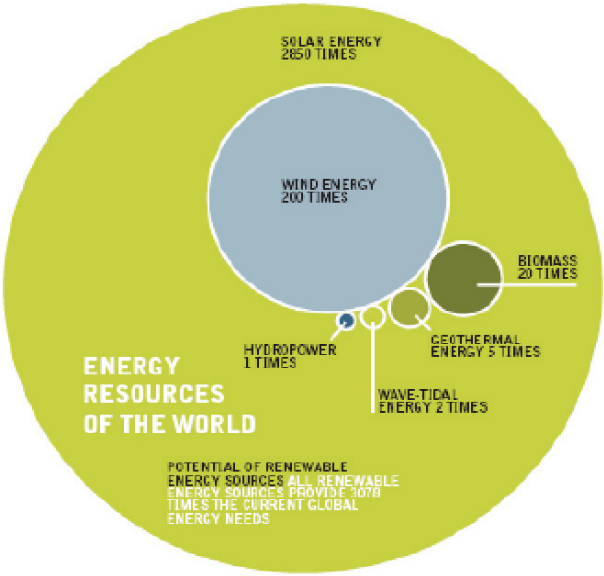

Figure 33. Availability of renewable energy sources on Earth (source: WBGU).

The following strategy paves the way for a future renewable energy supply:

- The phasing out of nuclear energy and rising electricity demand will be met initially by bringing into operation new, highly efficient, gas-fired combined-cycle power plants, plus an increasing capacity of onshore and offshore wind turbines and biomass. In the long term, wind is likely to be the most important single source of electricity generation.
- Solar energy, hydro and biomass will make substantial contributions to electricity generation. In particular hydro, solar thermal and geothermal, combined with efficient heat storage, are important elements in the overall generation mix. Cogeneration systems will be used as far as possible. Figure 34 shows the mix of renewable energies that can be achieved in 2030.
- The energy mix will include generators (gas turbine, hydroelectric, geothermal, biomass and others) whose electricity production can be controlled. Solar and wind experience intermittent generation. Wherever possible, an appropriate energy mix should be developed and various sources should be interconnected by means of “smart grids”, enabling unused electricity to be stored in batteries or transferred to other consumers or transformed. Such interconnexions are currently employed in large systems (buildings or industry). Other technologies have been developed where surplus intermittent electricity is used for the production of hydrogen by electrolysis; the hydrogen is stored for later use as fuel.
- Decentralized energy systems will be created, where power and heat are produced close to the point of final use, avoiding the significant waste of energy during conversion, transmission and distribution.

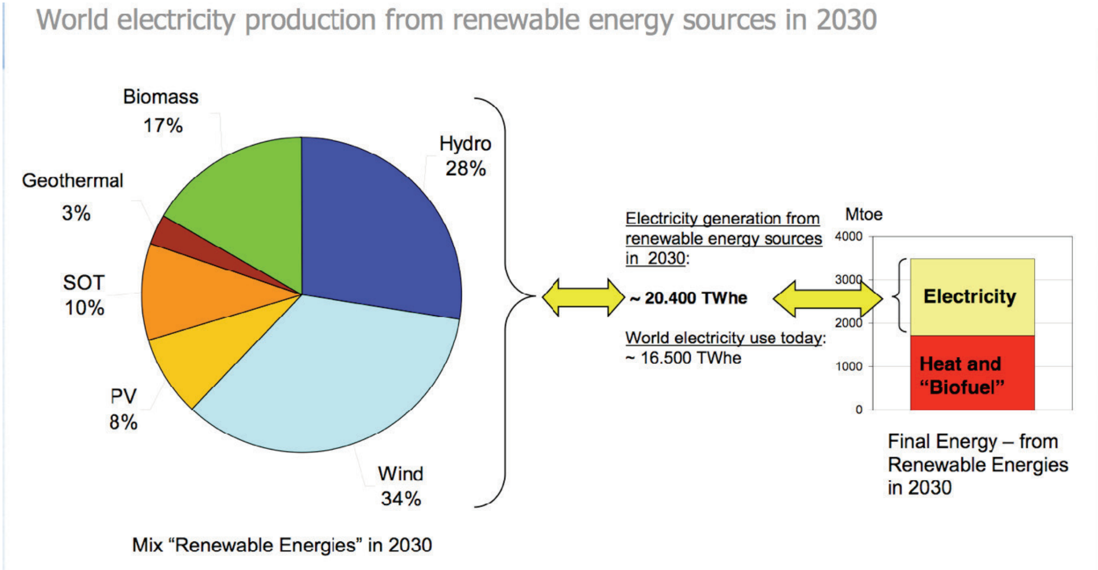

Figure 34. World electricity mix of production from renewable sources in 2030 (source: LBST, Alternative World Energy Outlook 2005).

As shown in Figures 35 and 36, city centres and suburban districts could become totally independent with respect to electricity and heat by using decentralized energy generation.

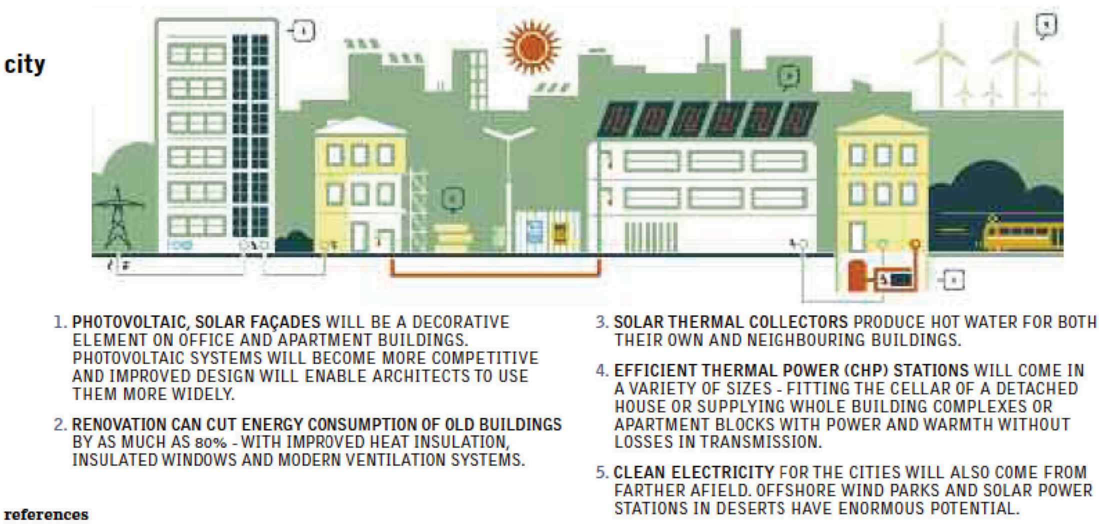

Figure 35. Decentralized energy production in a city centre (source: Greenpeace–EREC).

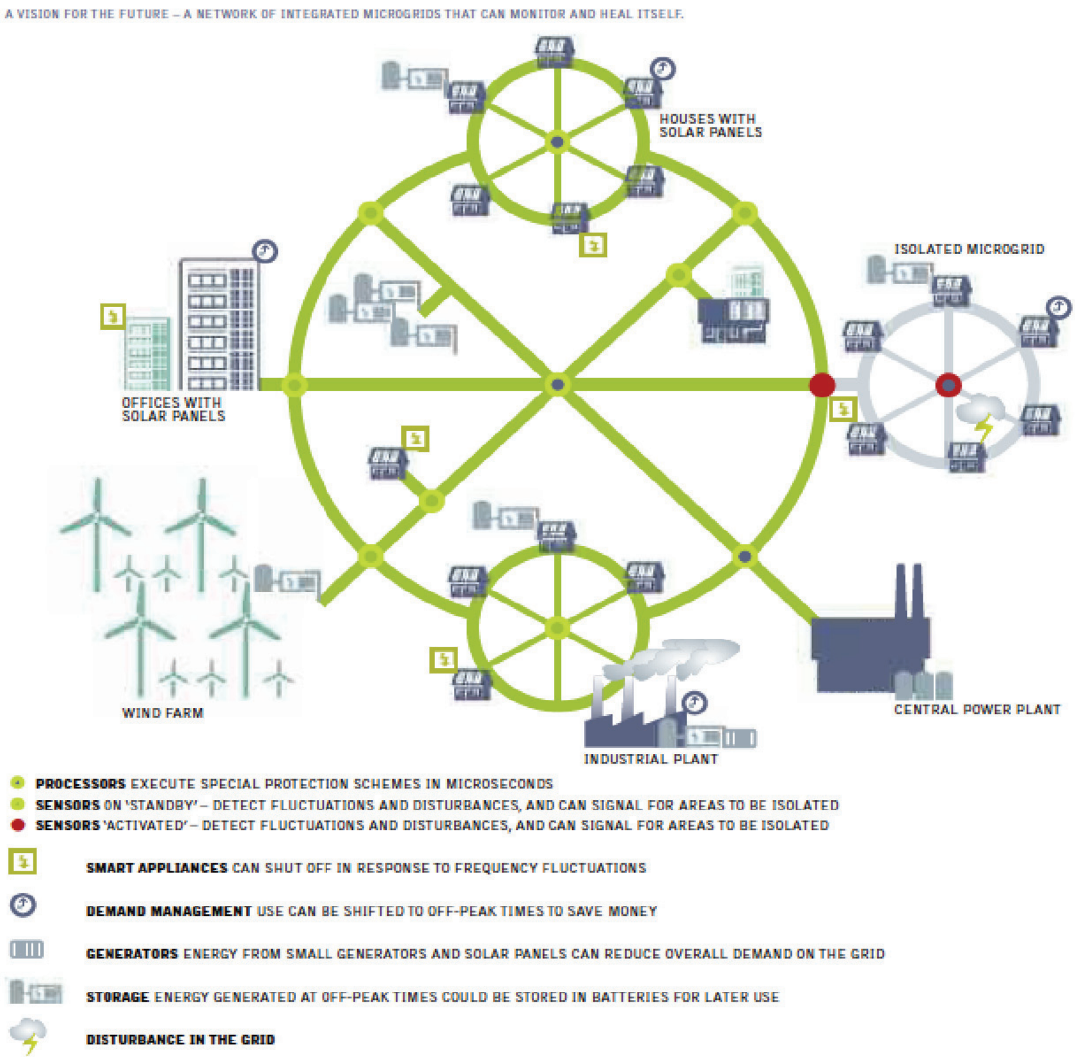

Figure 36. Network of an integrated grid for the optimal energy mix (source: Greenpeace–EREC).

9. The hydrogen economy[13]

Hydrogen is the cleanest fuel that can be found on the planet. It can be cofired with fossil fuels, it can be injected into biogas or methane pipelines, it can be used in fuel cells for power generation and transportation, it can be used as storage for the intermittent electricity produced by solar and wind and it can be employed in many branches of industry.

Unfortunately, the production of hydrogen is high in its energy requirements and these are currently mostly of fossil origin, thus making it environmentally unfriendly; in gas or liquefied

[13] "Where Will the Energy for Hydrogen Production Come From?—Status and Alternatives", by Ludwig-Bolkow-Systemtechnik GmbH—LBST/European Hydrogen Association.

form it is not easy to store due to its explosive character. However technology is under development to produce hydrogen exclusively with renewable energy, thus providing a totally CO2e-free clean fuel.

European research and industry are jointly associated in major research and technology development programmes to develop new production, storage and handling technologies as well as a large number of applications such as fuel cells for electricity and heat generation, ensuring that hydrogen fulfils its potential as the cleanest fuel for the future. In the area of fuel cells a large number of technologies are under consideration, utilizing different concepts and materials in order to improve the efficiency and to reduce the costs. It is expected that small portable applications will enter the market in the coming years and will help introduce the benefits of fuel cells and hydrogen to the general public. Large scale stationary and cogeneration fuel cells are already deployed today and their development is expanding industrially.

Transport applications will be the main driver for hydrogen demand; mass production of passenger vehicles powered by fuel cells could be in commercial production before the end of the decade for achieving significant replacement of fossil fuel-powered vehicles. A new hydrogen economy should begin to compete with and replace the fossil fuel economy in the near future. Figure 37 shows the technical potential of hydrogen sourced from renewables in the EU.

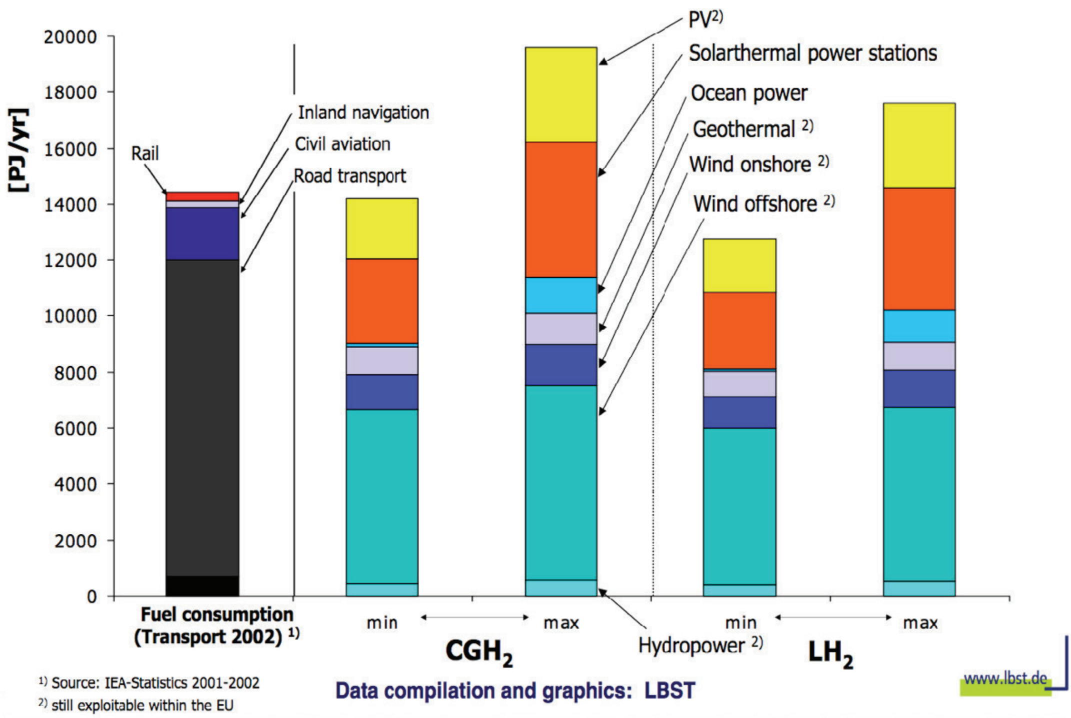

Figure 37. Technical potential for hydrogen from renewables in the EU (source: LBST).

10. Conclusions

The Industrial Revolution has brought immense benefits to all of humanity, but if human intervention is at the root of the impact of "greenhouse" emissions on climate change, it must be conceded that this same revolution is now destroying life on earth. At the same time, the progressive and inevitable exhaustion of finite fossil energy sources will have a major impact on energy production on the planet.

The "business as usual" scenario, based on the IEA's World Energy Outlook (2004–2013) projection, is not an option for future generations. CO2e emissions would almost double by 2050 and the global climate could—assuming that current models are valid—heat up by well over 2 °C. This is likely to have catastrophic consequences for the environment, the economy and human society. The major and very urgent issue is to reduce CO2e emissions by lowering consumption, using energy more efficiently, and making use of all available types of renewable energy, which are abundant on the planet (implying phasing out the "carbon society").

Within the energy sector, the renewables industry and their friends have—unsurprisingly—a clear agenda for changes that need to be made in energy policy to encourage a shift to renewable sources. Figures 38 and 39 show two interpretations of the future possible energy scenarios. The alarming warnings from the IPCC and in the Energy (R)evolution reports drafted during the past eight years by Greenpeace, the Global Wind Energy Industry and the European Renewable Energy Council show what may well be a viable path to preserve the planet and to save human beings from the potentially disastrous effects of the greenhouse gases that our industrial civilization has produced.

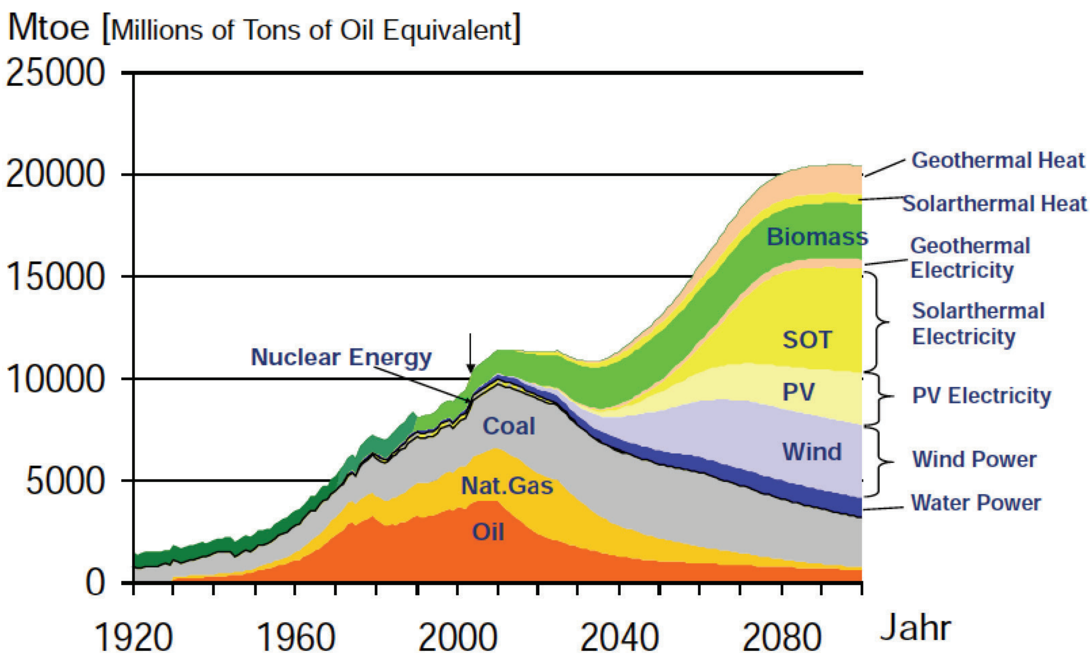

Figure 38. The world energy scenario (source: LBST Alternative World Energy Outlook, 2006).

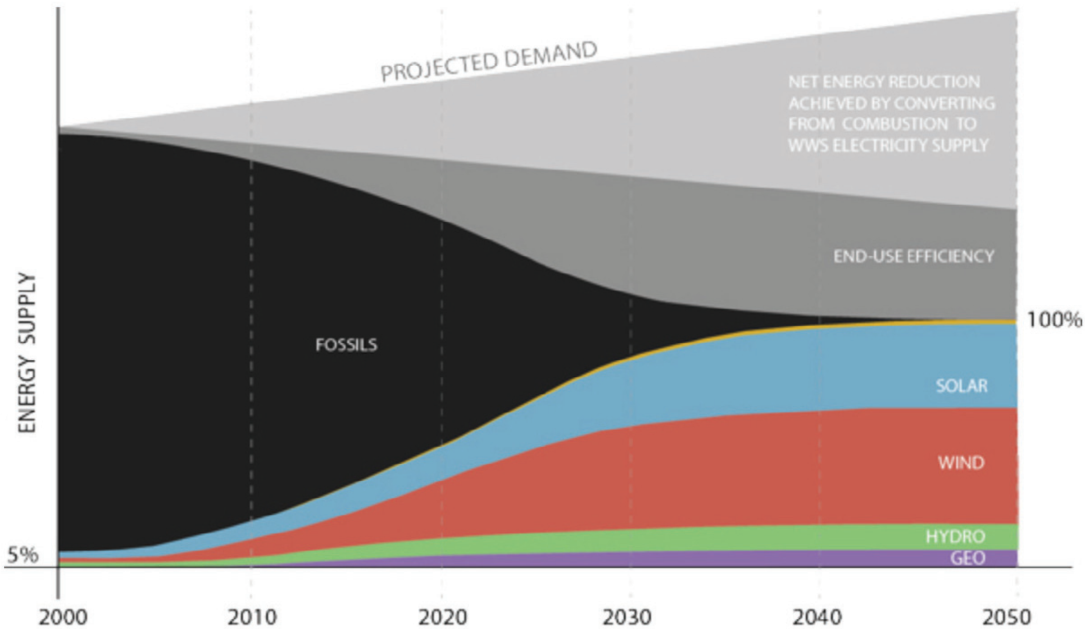

Figure 39. The future of energy on the planet (source: Mark Jacobson/ Karl Burkart).

It is hoped that society will accept this agenda and the authorities, wherever they are, will follow this acceptance and put in place and enforce legislation to protect the environment.

Climate change and the energy global security supply are extremely complex matters, heavily entangled in gigantic vested interests. Simple solutions are available but whether they can be put in place in time and whether they would indeed "save the planet" and the whole of humanity is another matter.[14]

[14] The author is grateful to Reinhold Wurster of LBST and Sven Teske of Greenpeace International for valued input to this paper.