Energy 40 (2012) 3–18

Contents lists available at SciVerse ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Sustainable energy development (May 2011) with some game-changers☆

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A R T I C L E   I N F O

Article history:
Received 19 August 2011
Received in revised form
19 September 2011
Accepted 26 September 2011
Available online 8 November 2011

Keywords:
Energy assessment
Peak oil
Sustainability
Sustainable energy development
Energy economics
ECOS 2011 World Energy Panel

A B S T R A C T

This paper presents the opening talk that briefly surveys the present (May 2011) situation in sustainable energy development. Recent estimates and forecasts of the oil, gas, coal resources and their reserve/production ratio, nuclear and renewable energy potential, and energy uses are surveyed. A brief discussion of the status, sustainability (economic, environmental and social impact), and prospects of fossil, nuclear and renewable energy use, and of power generation is presented. Comments about energy use in general, with more detailed focus on recently emerging game-changing developments of postponement of "peak oil", nuclear power future following the disaster in Japan, and effects of the recent global economy downturn of global sustainability, are brought up. Ways to resolve the problem of the availability, cost, and sustainability of energy resources alongside the rapidly rising demand are discussed. The author's view of the promising energy R&D areas, their potential, foreseen improvements and their time scale, and last year's trends in U.S. government energy funding are presented.

1. Introduction

This paper is intended to summarize key highlights of the global status at the writing of this paper (May 2011) of energy resources and use, related environmental effects, an unofficial review of the progress and plans in these areas by the U.S. administration, partly as reflected by its U.S. Department of Energy proposed fiscal year 2012 budget, and description of some possibly sustainable paths to the future. In accordance with the panel presentations format, these highlights are not always elaborated upon, but a broad list of useful references is given. Some of the basic references include the latest energy statistics annual report of British Petroleum (BP) for 2010 [1,2] [2], the excellent web sites of the U.S. Department of Energy (USDOE) [3], its Energy Information Administration [4], the International Energy Agency [5], and the International Atomic Energy Agency [6]. The analysis, interpretation, and comments are entirely the author's and do not represent any institutional or government views. Reviews of similar nature were published by the author in 2002 [7], 2006 [8], 2008 [9], 2010 [10], and 2011 [11,12] to update the information about this very dynamic field.

2. An executive summary

2.1. Critical global information

Energy resources and consumption are intimately related to environmental quality and other vital resources such as water and food. The energy situation must be viewed in that context, and some of the related key global data are therefore shown in Table 1.

2.2. Energy resources and consumption: significant changes relative to last year

➢ After a world primary energy use drop by 1.1% in 2009, which followed years of consistent rise, 2010 has seen an increase of 5.6% (Fig. 1), the highest since 1973, at least partially due to at least partial recovery from the economic downturn in 2008–2009 (especially in China and India) and as the large developing countries in Asia keep improving their standard of living. Energy consumption in 2010:
  - China's rose by 7% (lowest since 2002), the U.S. rose by 4.8% (notably after a 5% drop in 2009) and India's by 4.2% (lowest in recent years).
  - It rose even in all other countries that have in 2008 exhibited a drop, such as the EU, Japan, and Australia [1,12,20].

☆ Invited keynote paper from the 24th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems – ECOS 2011.

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[2] While British Petroleum (BP) has published the Annual Statistical Review of World Energy for 60 years without significant challenges, and serves most frequently as the source of the proved fuel reserves data, the accuracy is unknown and is subject to large errors. Comparison with other information sources shows some differences.

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doi:10.1016/j.energy.2011.09.044

Table 1
Some key data during the period 2006–2010.

Item	Global amount
Total primary energy use (2010)	502 EJ [1]
Industry	30% [12]
Transportation	29% [12]
Residential	22% [12]
Commercial	19% [12]
Electricity	40% [12]
Electric power installed (2008)	4.4 TWe [13,14]
Electricity generated per year (2010)	21.3 PWh = 77.2 EJ [1]
People without electricity (2009), billion	1.44 [13]
Global temperature change, °C	
industrial period	+0.76, exponential rise[a] [15,16]
2006–2010 average	−0.04 [15]
Water shortages [17,18]	884 million people lack safe drinking water, 2.5 billion people have inadequate access to water for sanitation and waste disposal, Ground water depletion harms agriculture
Food shortages	925 million undernourished people (1 in 7)[b] [19]

[a] The temperature increase per decade is more than twice as fast as that observed over the preceding hundred years.
[b] An encouraging drop of 9.4% relative to 2009; It is noteworthy that at the same time 1.9 billion people, twice as many and rapidly rising, are overweight [20].

- In Organisation for Economic Cooperation and Development (OECD) countries it rose by 3.5%, the strongest growth rate since 1984, U.S. rose by 4.8% (notably after a 5% drop in 2009), non-OECD grew by 7.5%, China's grew by 11.2%, and India's by 9.2% (highest historically).
- A few smaller OECD countries had slight drops in energy consumption: Norway 3.7% (it is one of the highest per capita consumers anyway), Switzerland −2.4% and Greece −2.4% [1,12,21].

➢ The reserves-to-production ratio (R/P) remains rather constant: ~40 for oil (rose to 47 in 2010), ~60 for gas, and 120+ for coal, and mostly rising! (Figs. 2–4). There probably exists sufficient oil and gas for this century and coal for 2 or more.

➢ Tar sands and oil shales are becoming more attractive and available in quantities probably exceeding those of oil and gas; most notably large amounts of shale gas have been discovered and are increasingly being exploited (Section 3.2.1.3 below).

➢ Nuclear power produces ~14% of world electricity; the number of reactors is increasing very slightly [6] but the recent nuclear disaster in Japan has placed nuclear power development in at least temporary limbo, more about it in Section 3.4 below. The 2009 stoppage in the U.S. of the development of the U.S. Yucca Mountain long-term nuclear waste storage facility [22–24] is another serious setback to nuclear power development, at least till a satisfactory storage alternative is found.

➢ Renewable energy can satisfy at least two orders of magnitude more than the world energy demand (cf. [10,11]), but negative impacts aren't inconsequential (cf. [25,26]).
- Wind, geothermal, solar, biomass and waste energies satisfy only 1.8% of global energy consumption
- Wind and solar photovoltaics (PV) are continuing their exponential growth as costs decrease and with the strong support from government incentives.
- The renewed interest in solar–thermal power is continuing with additional installations.
- Biomass energy has an important role but questions about its sustainable use continue increasing (cf. [10,11]), placing now more focus on use of inedible biomass and algae.
- Geothermal energy continues deserving more attention (cf. [27,10,11]).

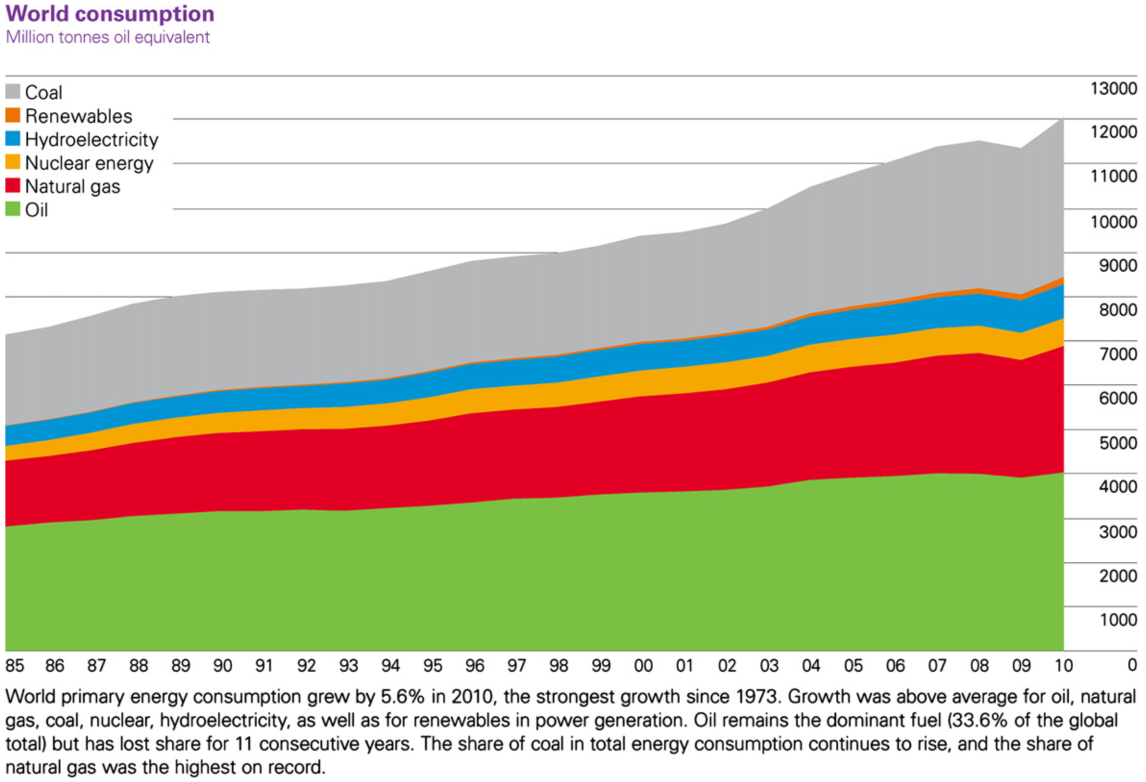

Fig. 1. World primary energy consumption 1985–2010 [1].

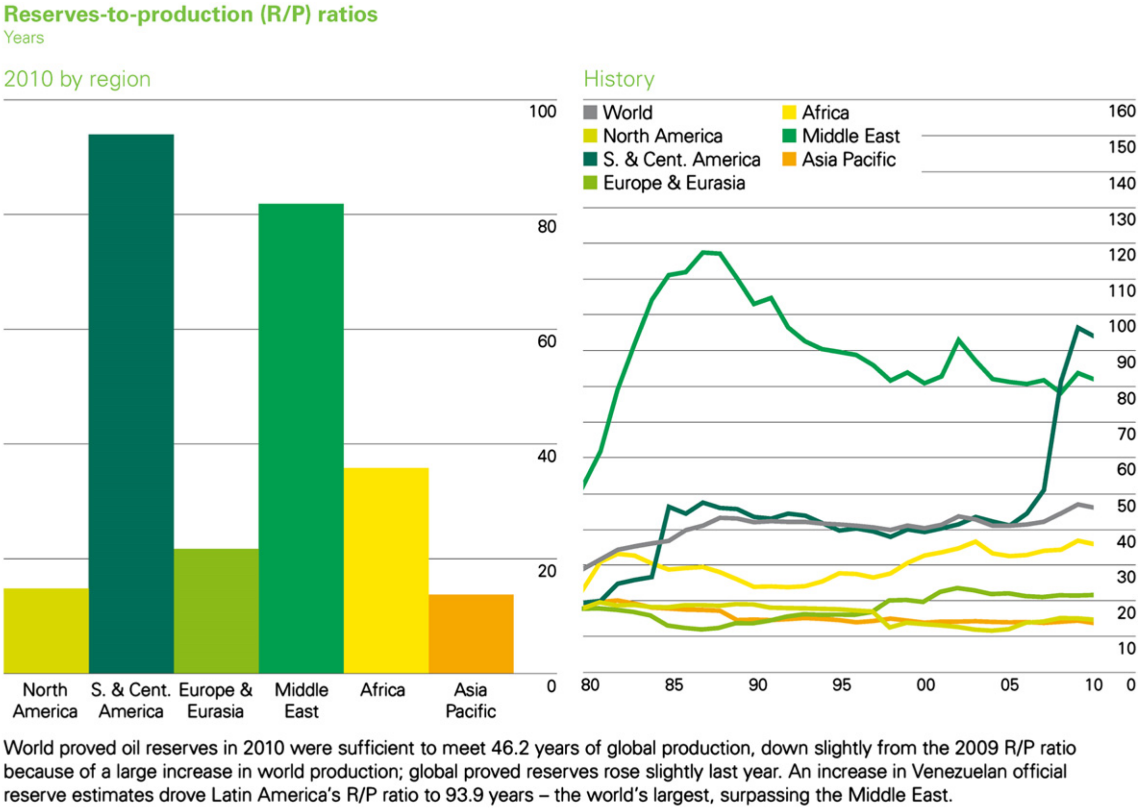

Fig. 2. The oil (proved reserves)-to-production ratio (R/P), 1980–2010 [1].

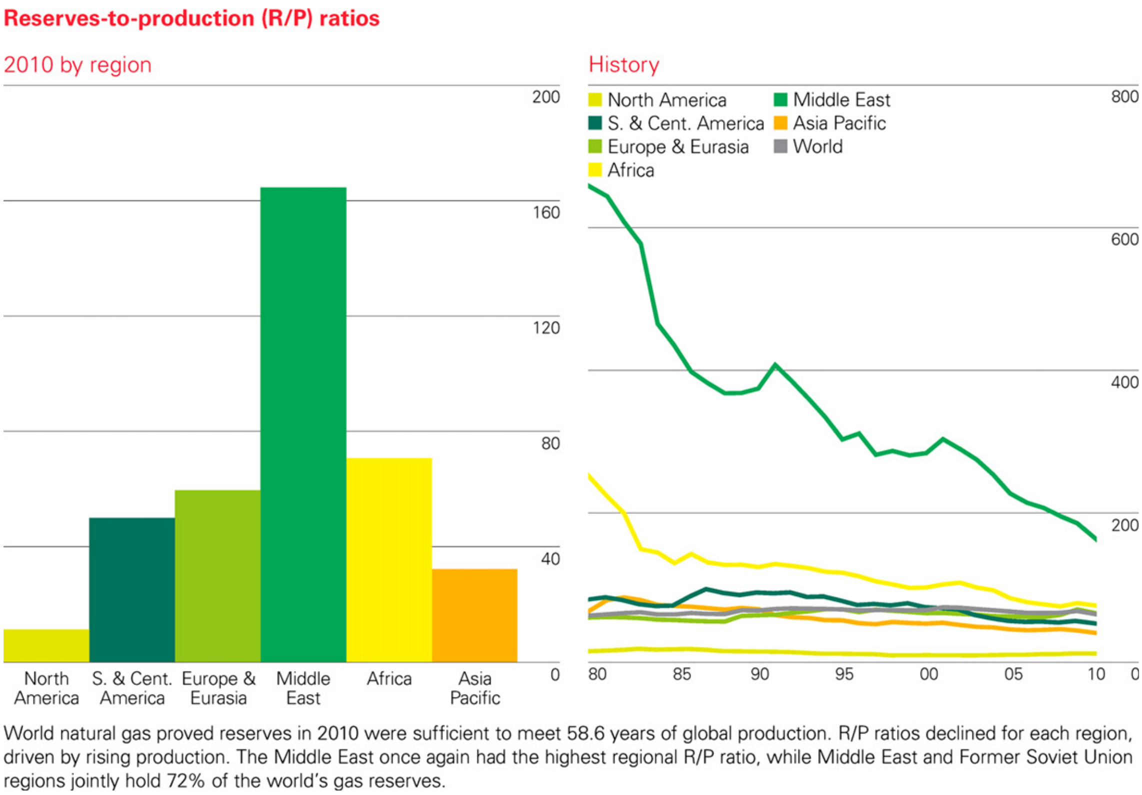

Fig. 3. The gas (proved reserves)-to-production ratio (R/P), 1980–2010 [1].

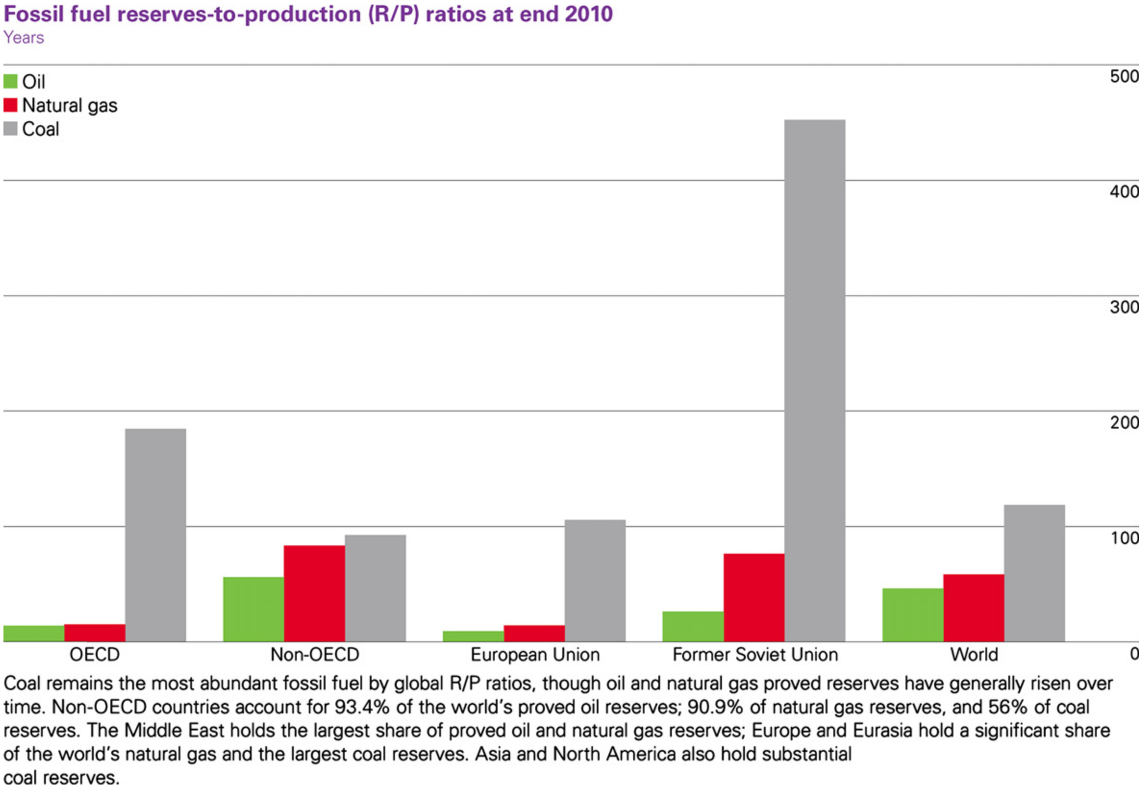

Fig. 4. Fossil fuels (proved reserves)-to-production ratio (R/P), 2010 [1].

  - The frequently deceitful and unscientific promotion of renewable energy, which usually emphasizes growth rates rather than realistic unsubsidized costs and aggregate sustainability, plays on public sentimentality, and sometimes unjustifiably dismisses and even demonizes the practical significance of the competing conventional energy sources, does much damage to the credibility of this vitally important energy source.
- While hydrogen and fuel cells continue to be valuable in the energy portfolio, global interest and funding are waning.
- The plug-in electric or hybrid car seems to be the preferred route to private transportation. Improvement of traffic management, roads, and public transit are at least as important but don't receive adequate attention. The newly discovered gas resources point to increased interest in its use as vehicular fuel, mostly in nearly-conventional internal combustion engines.

2.3. Future electric power generation

- A most imminent challenge is that expected demand for electricity would require during the coming two decades the installation of as much power generation capacity as was installed in the entire 20th century.
  - One 1000 MW plant every 3½ days
  - e.g., China is adding already one coal-fired 1000 MW plant each week [1].
  - The global electric energy generated growth in 2010 was a record of 5.9%.
  - After past drops, it rose again in the US by 4.3% and in EU by 3.7% and continued rising in India by 6.0%, and in China by the record 13.2%; the highest regional growth was in Asia-Pacific, 9.1%.
- While the plug-in hybrid electric car and electric-driven public transportation seem to be the most promising ways toward energy-efficient transportation, this would further raise the global demand for electricity in a most significant way, perhaps by 25% [11], but timing of charging the vehicles, if at periods of low electricity demand, could in fact improve grid efficiency and end up having a relatively small impact on required grid capacity [28].
- Because of its abundance in the most energy-consuming countries such as China, the USA, parts of Europe, India, and Australia, and the currently relatively low cost of power generation when using it, coal is likely to be increasingly the main basic fuel for power generation, partially after conversion to gaseous or even liquid fuels, with the reduced emissions IGCC (Integrated gasification combined cycle) plant receiving major attention but still making slow progress to large-scale commercialization.
- The combined cycle (CC) power generation plants are the most desirable; having efficiencies of up to about 60% even at present, less emission than other plants when using natural gas, and reasonable cost that would keep decreasing as the technology advances further. The rapidly increasing availability of gas is bound to also rapidly increase CC power generation.
- The technology and capacity for CO_2 capture in fossil fuel power generation is within reach, but for sequestration of the CO_2 is not yet (cf. [29,30]).
- Despite the unresolved problems of waste storage, proliferation risk, possible shortage of fuel for conventional reactors, and safety (that was perceived to be dormant since some time after the Chernobyl disaster in 1986 but woke us up with a vengeance in the recent nuclear disaster in Japan), nuclear power plants are likely to be constructed, at least for special needs.
  - Interest is growing in small modular (light water reactor, LWR) nuclear reactors (SMR) of 40–300 MWe capacity built

offsite and shipped to site [31], but their advantages have not yet been demonstrated.
  - Following the recent nuclear disaster in Japan, future development directions and magnitudes of nuclear power are being re-examined, Japan shelved the plans for construction of 14 nuclear power plants and is focusing on strong reduction in demand combined with strong increase in renewable energy and is likely to use more gas-fired CC power generation plants, and in some countries (Germany, Switzerland) moratoria on nuclear power have been imposed.
  - The competition to nuclear power is also advancing, mostly from the large amounts of gas being found that can be used for the highly efficient combined cycles for power generation, and from the push for more massive use of renewable energy.
- Wind power generation will be deployed rapidly and massively, but will be limited to regions where wind is economically available, and will be limited by the extent and quality of the electricity distribution grid.
- Photovoltaic power generation will continue increasing in efficiency and decreasing in price, and being employed in many niche applications, but being three to five times more expensive now (unsubsidized) than other power generation methods, and also limited by the extent and quality of the electricity distribution grid, and even by availability of materials, it may not reach parity in the coming decade.
- Geothermal power generation requires significant R&D investment to reach the next level of deployment but deserves much more attention as a viable and potentially abundant renewable energy source.
- Effective storage of energy, and of power plant-magnitude electricity in particular, are off essential importance for improving electric power generation efficiency and for incorporating intermittent electricity sources such as wind and solar; Improvements and technological advances in the distribution [32] and storage of electric power will continue and should be advanced much faster.

2.4. Environmental and food impacts of energy

- Global temperatures are generally rising over the past 50 years on average at an unprecedented and exponential rate, alongside with similar rises in greenhouse gas (GHG) emissions; there is clear evidence of major melting of polar ice caps, glaciers, and snow caps; on a shorter time scale, however the 5-year land and ocean average temperature during the 2006–2010 temperature dropped by 0.04 °C relative to the 2001–2005 period [16], perhaps due to La Niña in the recent period (or melting of polar caps?).
- Emissions continue to grow and CO_2 concentrations had increased to over 390 ppm, or 39% above preindustrial levels, by the end of 2010 [14,33].
- The water and food supply are in crisis, with about 1 in 8 people lacking safe drinking water, 1 in 2 lacking access to for sanitation and waste, and 1 in 7 being undernourished (Table 1).
- Energy and water use are strongly interdependent:
  - Energy development depends on water use very heavily, in all its stages: mining coal, oil and gas drilling, mining and processing tar sands and oil shales, fuel processing and transportation, manufacturing of energy-related equipment, cooling of thermal power plants, hydropower and marine energy, and treatment of energy-related emissions, among others; about 20% of the world's water withdrawals are used for industry and energy [34].
  - Similarly, water use depends heavily on energy: well drilling and water transportation, water desalination, waste water treatment, use of water in agriculture, and so on; e.g., energy can account for 60–80% of water transportation and treatment costs and 14% of total water utility costs [34]. The recent acceleration in the production of biofuels adds to the pressures on water resources; e.g., up to 3500 L irrigation water are needed per liter ethanol produced from biomass, including both water for growing the biomass and processing it to fuel.
- Conversion of food-to-fuel endangers the food and water supply and raises their price (see some details in Ref. [10]).
- The "Living Planet Index"[3] is estimated to have declined since 1970 by about 30%, and the "Ecological Footprint"[4], increased 2.4-fold in the same period (cf. [35]): we seem to be *running out of environment much faster than out of resources.*

2.5. Economic/financial implications

- A major concern (or opportunity?) is that the price of oil (Fig. 5) was generally growing very rapidly, from $28/barrel in 2003, to $38 in 2005 and occasionally to above $80 in 2006 and peaking at $147 in 2008, precipitously dropping to $36 by the end of 2008, and then rising to $121 by May 2011 with drops to as low as $68 [1,12]; Natural gas prices grew strongly in the UK and in markets indexed to oil prices (including much of the world's liquefied natural gas, LNG); but prices remained low in North America – where shale gas production continued to increase – and in continental Europe (partly due to a growing share of spot-priced deliveries) [12,13].
  - The large fluctuations are very large, up to 4 times the stable minima.
  - The oil peak price remains one to two orders of magnitude higher than the cost of extraction, possibly meaning that financial speculation is overwhelming supply and demand, and all technical improvements.
  - Gas and coal prices track to some extent the oil prices often even when they aren't competing fuels.
  - The combination of these effects is a severe and perhaps insurmountable barrier to the development of non-fossil fuel energy sources such as renewable and nuclear.
- The global economic turndown in 2008 caused the stock market to drop by up to 45% (MSCI World Index [36]) but the world GDP PPP per capita between 2007 and 2009 dropped by only 1.5%, the world primary energy consumption per capita dropped 3.5%, and the CO_2 emissions dropped by1.5% [4,12–14,37,38].
- Many countries, especially the developed ones, show evidence that national GDP can be increased without increasing energy consumption whereas most developing countries seem to increase their energy demand along with national GDP growth.
- Globally, costing of energy resources remains inequitable, as it doesn't include subsidies, environmental impact, and other consequences [14].
- The investments in energy R&D remain much too low, less than half a percent of the monetary value of the energy use, to meet the future needs.

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[3] The *Living Planet Index* tracks populations of 1686 vertebrate species – fish, amphibians, reptiles, birds, mammals – from all around the world.

[4] The *Ecological Footprint* is the area of biologically productive land and water needed to provide ecological resources and services – food, fibre, and timber, land on which to build, and land to absorb carbon dioxide released by burning fossil fuels.

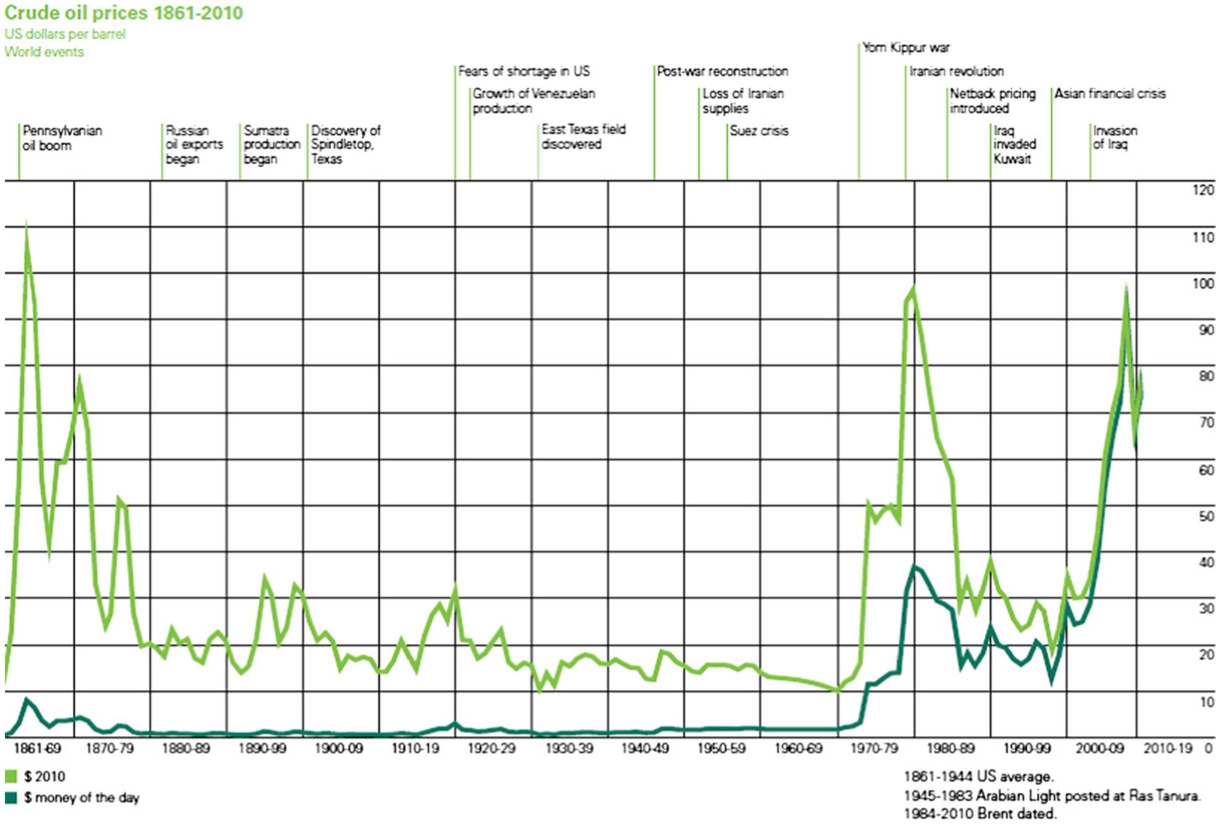

Fig. 5. Crude oil prices from 1861 till 2010 [1].

2.6. *Social aspects*

- ➢ Compared with the year 2010, the World population is predicted to rise by 35% by 2050 [39]; This estimate is based on the current trend of slowly declining population increase rate, but some populous countries are at this time encouraging their population growth or implicitly allowing it, so the population increase may in fact be much larger. New generations consume on average more energy per capita than their parents did.
- ➢ Many governments of the world are subsidizing energy conservation, development of renewable energy, and reduction of greenhouse gas emissions to some extent. While the intent is very positive, the outcome is not always so because political creation of artificial economies is unstable and misleading, and often not well planned, especially in regard to longer-term broader effects.
- ➢ There is a huge and socially ominous national disparity [1,40] demonstrated by the range of 5.7 (Eritrea) to 788.3 (Qatar) GJ/capita/year (Fig. 6), especially significant since it has the highest populated nations at the top of energy poverty, a disparity that stymies human development of the energy-poor nations and is a trigger for conflict.
- ➢ Energy's increasingly important role in economics, accompanied by government interventions that are at times not well thought out, and by international strife and competition that ignore global sustainability threats, give rise to massive fraud by entire countries, companies, and individuals, and to breakdown of free markets, as demonstrated for example by the Enron scandal, by the financial systems' bankruptcies that led to the current economic turndown, and by the wildly fluctuating oil prices that are unrelated to supply and demand.

3. Some recent game-changing events

3.1. *"Game-changer" introduction*

The energy field is very dynamic, and beside the gradual commonly-anticipated changes, sometimes also exhibits some relatively rapid and major game-changing events. The frequency and impacts of such game-changers, whether they are in demand, supply, resources, price, environmental impacts, social impacts, and/or technology, is increasing alongside with the magnitudes of these factors. Obvious major past examples of such game-changers include a wide use of technology to convert solid fuels to fluid ones and development of the jet engine (during the Second World War), massive political impact on oil and gas supply and price (OPEC and the embargo of the 1970-s), concern about possible imbalance between rapidly rising fossil fuel demand and its limited availability ("Peak Oil"), and from about 1979 [41,42] sweeping concern about anthropogenic global warming and related activities to prevent it. Although some of these events or at least their importance could have been anticipated with careful and timely examination, their recognition was relatively sudden and caused global upheavals.

Three of such game-changers that came to realization in the past few years are the apparent postponement of the threat of depletion of fossil fuels (or "Peak Oil" for short), new realization of the strong impact of economics on energy use and related emissions that arose from the recent global economy downturn, and the realization of the vulnerability of nuclear power as exhibited by the recent

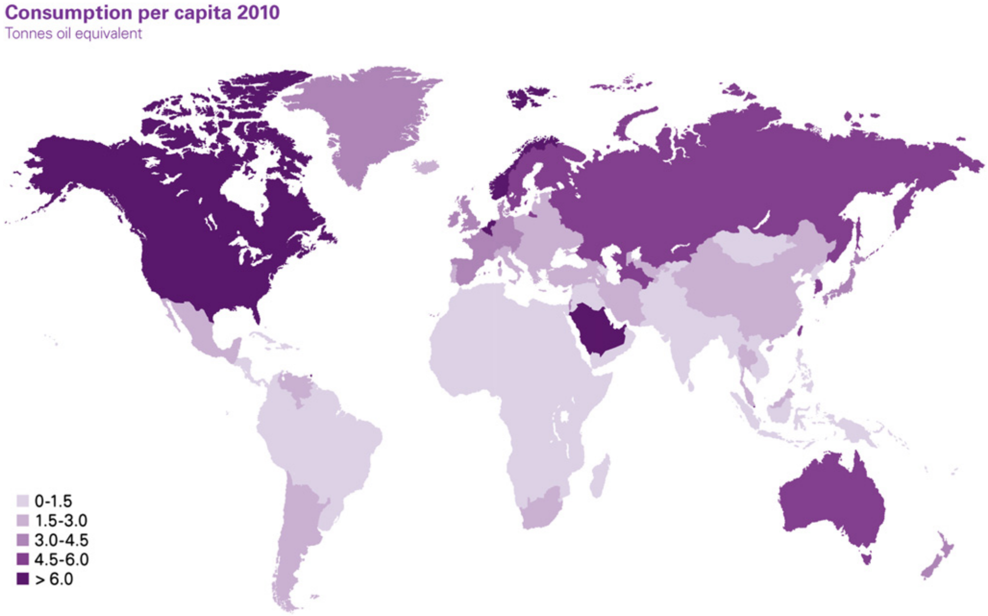

Fig. 6. World per capita primary energy consumption distribution 2010 [1].

tragic nuclear disaster in Japan. These events are discussed below in a little more detail.

3.2. End of fossil fuels postponed?

3.2.1. "Unconventional" fuels

3.2.1.1. General introduction. Recognizing that careers and national and global plans were invested in peak oil and fossil fuel depletion theories, it is now increasingly acknowledged that the last few years have experienced the discoveries and exploitation technology of large amounts of fossil fuels, that include to some extent additional exploitable conventional oil, gas, and coal, but to large extent "unconventional" fuels led by tar (oil) sands, "extra heavy" crude oil, coal bed natural gas (CBNG)[5], "Tight Gas"[6], recently shale gas and potentially shale oil, as well as large (but also very difficult) resources of methane hydrates [43]. The quantities of these unconventional fluid hydrocarbons are estimated to be significantly larger than of the conventional ones.

Although at quantities and locations not exactly known and clearly more expensive to beneficiate, vast amounts of "conventional" oil and gas are still beleived to be available, in clearly more difficult environments such as very cold climates, deeper offshore locations, and more environmentally fragile regions [1,12–14]. Their ultimate use will depend on cost that must include all externalities, especially those of proper environmental care.

The vast "unconventional" hydrocarbon resources pose significantly higher negative environmental impacts than the conventional ones, and typically not only do not reduce global greenhouse gas emissions via fuel substitution, but even increase them. These problems can be alleviated with proper technology at a higher product cost, and environmental protection governmental regulation must be properly formulated and enforced prior to commercial exploitation and use. A brief description and status the already commercially exploited tar (oil) sands and shale gas, and the largely unexploited shale oil follows.

3.2.1.2. Tar (oil) sands. Tar sands (Canada prefers to call them oil sands) are porous sands containing bitumen (8–12% in the Canadian Athabascan tar sands) and water. There the overburden consists of 1–3 m of water-logged muskeg (bog soil) on top of 0–75 m of clay and barren sand, while the underlying oil sands are typically 40–60 m thick and sit on top of relatively flat limestone rock. The production of one barrel of crude oil there requires the processing of ∼2 tons tar sands and removal of ∼3 tons overburden, as well as the use of 7.5 to 10 barrels water. Typically 40 to 70% of the water is (or can economically be) recycled, resulting in a net water use of 2.5 to 4.5 bbl per bbl oil, which could be reduced by further increase of recycling. About 20% of the produced crude oil energy must be invested (currently mostly as natural gas) in the process. Overall, the CO_2 emissions associated with the final product, such as automotive gasoline, are at least 20% higher than those when conventional oil is used.

Oil sands are found in at least 70 countries, but so far it is thought that the largest deposits are in Canada, (Alberta), which exploits them aggressively and is already producing about 1.5 million barrels of crude oil per day from them, mostly exported to the US, and planned to be increased to 3 million bbl/day by 2018 [44]. The Albertan technically recoverable reserves are estimated by the Alberta government at 171 Gbbl [44] (and by others at 280–300 Gbbl), second only to (or larger than) the optimistically estimated Saudi Arabian oil reserves (260 Gbbl) and can be 13% (or up to 23%) of total current global crude oil production. The total reserves of Alberta, including oil not recoverable using current technology, are estimated at 1700–2500 Gbbl, much higher than the total proven global oil reserves. The U.S. tar sands resource in place is estimated to be 60–80 billion barrels of tar sands. About 11 billion barrels of U.S. tar sands resources may ultimately be recoverable [45].

Using the current procedures, which appear to devastate at least the local environment, the operating cost of tar sand crude oil is

[5] Wells produce from relatively shallow coal seams which act as a source and reservoir of the natural gas, frequently producing water alongside. The gas was formed by thermogenic alterations of coal or by biogenic action of indigenous microbes on the coal. There are some horizontally drilled CBNG wells and some that require hydraulic fracturing. At this time the use of CBNG in the US is large, roughly the same as that of shale gas or non-associated gas [12].

[6] Wells produce from regional low-porosity sandstones and carbonate reservoirs.

below $30/bbl with the total cost estimated to be about $60/bbl, and at most $75/bbl [46]. Addition of costs associated with complete removal of lasting environmental impacts, removal of explicit and implicit government subsidies and fair adjudication of social challenges by indigenous populace would raise the total cost significantly [47].

3.2.1.3. Shale gas [48,49]. Shale gas is a natural gas (primarily methane) that is contained within low porosity, low permeability shale rock, most often found at depths of 2 to 4000 m below the earth surface. It is available in many countries. The shale is brittle and releases the gas when fractured. The fracturing is accomplished by drilling vertically to the shale layer, and then swiveling the drill to a horizontal direction to drill along that layer for typically 300 to 1500 m. Horizontal drilling reduces significantly the extent of surface impact commonly associated with multiple vertical wells drilled from multiple well pads. Further reduction can be achieved by "wagon-wheel" style of drilling. In this method a central command center is set up over areas rich in shale gas and the drilling process is begun from this central location. Once a supporting bore hole is drilled to the appropriate depth, "spokes" of the wagon wheel are drilled into different azimuthal directions off that central bore hole, making it easier to drill, fracture, and extract the gas from this point versus drilling several bore holes. Not only is less land area used, fracture fluids are only inserted (and thus taken out) from one point, and there is greater control over each horizontal bore.

A fracture fluid, typically pressurized to 34 to 50 MPa ($\sim$5000 to 7000 psi) is pumped down into a drill-bored hole, causing the shale to fracture (hydraulic fracturing, or "fracking", used for various applications since the early 1940-s) and the natural gas trapped inside it to be released, extracted and then harvested and refined at the surface. Escape of the gas and protection of the ground water during fracking is by a combination of the casing and cement that is installed when the well is drilled, and the layers of rock naturally present between the fracture zone and the outside and any fresh or treatable aquifers. The fracture fluids are water based mixed with additives that help the water to carry sand proppant (it maintains (props) gas flow cracks open) into the fractures. Water and sand make up over 98% of the fracture fluid, with the rest consisting of various chemical additives that improve the effectiveness of fracking, which typically include hydrochloric or muriatic acid (to dissolves carbonate material in the rock), ammonium bisulfate (oxygen scavenger), glutaraldehyde (biocide), NaCl (breaker), N,n-dimethyl formamide (corrosion inhibitor), petroleum distillate or diesel (friction reducer), guar gum or hydroxyethyl cellulose (gel), 2-hydroxy-1,2,3-propanetricaboxylic acid (iron control), ethylene glycol or 2-butoxyethanol (scale inhibitor), and fluorocarbons, napthalene, butanol, and formaldehyde have also been used.

The amount of water needed to drill and fracture a horizontal shale gas well is generally about 10 to 18 Mm^3 (2–4 million gallons), depending on the basin and formation characteristics.

After drilling and fracturing of the well are completed, water is produced along with the natural gas. Some of this water is returned fracture fluid and some is natural formation water. These produced waters that move back through the wellhead with the gas represent a stream that must be managed. The stream contains ingredients from the natural soil disturbed by the drilling and fracking such as brine, gas and liquid/solid hydrocarbons, metals, and naturally occurring radioactive materials (U, Th, Rn), as well as most of the chemicals that were introduced with the fracking fluid. Furthermore, some of the gas escapes to the atmosphere adding to global warming, and some ends up in water supplies, in either case posing risks of fire, explosion and toxicity [50]. Contamination of aquifers, watersheds, lakes, streams and soil are possible and take place unless proper management techniques such as underground injection, treatment and discharge, and recycling, are used [51]. There is a widespread feeling that the shale gas companies and the individuals from whom they lease the sites are sometimes eager to exploit the gas without adequate environmental protection, and that enforcement by the local and national governments is rather inadequate, partly because this is a relatively new energy source. Much pressure is applied by the public to establish proper legislation and enforcement, and it is often opposed by the beneficiaries, including gas producing land owners who are in many cases local small farmers. It is also estimated that the entire process of shale gas mining and use triples GHG emissions relative to the gas combustion alone.

The first producing shale gas well in the U.S. was completed in 1821 in Devonian-aged shale near the town of Fredonia, New York. Recently shale gas production in the United States rose, and keeps rising, exponentially: from 11 Gm^3 in 2000 to 138 Gm^3 in 2010, i.e. a 12.3-fold rise in 10 years, to 23% of U.S. dry gas production.

The shale gas resource is estimated to be immense [52]: for the US, the total technically recoverable natural gas resource base is 72 Tm^3 (or up to 98 Tm^3 according to some estimates) of which the shale gas resource is 24.4–49.4 Tm^3. This can imply that at the U.S. current production rates of about 0.6 Tm^3/year, the current recoverable shale gas resource estimate provides enough natural gas to supply the U.S. for the next 41 to 82 years (some estimates claim more than a 100 years), with the understanding that the number of years depends on the rate of consumption, which is likely to increase especially as gas is used more intensively for power generation, and on the rate of discovery of recoverable shale gas (fields, and technology to access them properly), which is increasing too. The total world proven reserves of natural gas are about 187 Tm^3, and technically recoverable are roughly 453 Tm^3, both largely excluding shale gas, while in a recent study of shale gas resources in 32 countries [52], theirs were estimated at 187.5 Tm^3. Since the studied countries did not yet include many high potential ones such as Russia, much of Eastern Europe and of Africa, the Arab Peninsula, Iran, Iraq, Kazakhstan, Azerbaijan, Malaysia, Thailand, Burma, Laos, Cambodia, Vietnam, Indonesia, Philippines, Mongolia and Greenland, among others, this estimate is much lower than the potential total. Thus, adding the identified shale gas resources in just these 32 countries to other gas resources increases total world technically recoverable gas resources by over 40% to at least 640 Tm^3. If indeed recovered, these gas resources would be sufficient for 203 years at the 2010 annual World gas consumption rate of 3.15 Tm^3.

3.2.1.4. Shale oil [45,53–57]. Shale oil is typically a matrix of marlstone (dolomite, calcite, quartz) that contains kerogen and bitumen. Kerogen (90% of the organic matter) is insoluble in normal organic solvents because of its huge molecular weight (>1000 Daltons) with bitumen being its soluble portion. Separation consists of crushing the shale, separating the organic matter from the stone, usually by a hot water–alkaline solution, and letting the organics float to the top, unaerobically heating the organics to $\sim$500 °C to break the long hydrocarbon molecules into smaller ones, and then separating those to useful fractions by distillation.

The production of one barrel of crude oil from the main US shale resources requires the processing of 1.4–8.4 tons oil shales, as well as the use of 7.5 to 10 barrels water. Some of the water can economically be recycled. Energy must be invested in the process of mining and conversion, resulting in an estimated energy return ratio of 0.7–13.3 [58], realized in actual practical projects to be 3–10 [54,59]. Overall, the CO_2 emissions associated with the final product, such as automotive gasoline, are at least 20% higher than those when conventional oil is used.

The whole process is associated with significant environmental problems, due to the need to move very large amounts of natural materials, leaching of spent shale (alkaline) by runoff water, air pollution due to mining and retorting, large water use, and contaminated waters outflow. Emitted to the air and water are various contaminants, including sulfur, mercury, SO_x and NO_x and some radioactive compounds.

Oil shales are quite abundant worldwide, led by the US (72%) and followed by Russia, Brazil, Jordan, Morocco, Australia, China, Estonia and Israel (in that order), among about 26 others.

The U.S. Department of Energy estimates [45,53,57] that recoverable oil shale in the Western United States amounts to ~2000 billion barrels of oil (vs. 260 billion barrels of oil that Saudi Arabia claims to have) and is assessed at present as the richest and most geographically concentrated oil shale and tar sands resource in the world. The global reserves are estimated at 3300 billion bbl [54], sufficient to last the world for 104 years at the current oil consumption rate of 31.9 billion bbl/year.

Sizable oil shale-fired power plants exist in Estonia, which has an installed capacity of 2967 MW, Israel (12.5 MW), China (12 MW), and Germany (9.9 MW). Production costs were estimated to be up to $100/bbl crude oil, with some predictions that it could be maybe one-third of that for in situ conversion (that hasn't been tested even in prototype scale yet) [57].

3.2.2. Demand-side effect on "peak oil"

Depletion of fuel resources depends of course not only on the magnitude of the resource but also on the demand rate. Demand is very difficult to forecast because it is affected by important objective parameters such as price and its regulation level, efficiency, technology, and government intervention to support national fuel independence or new export and employment potential.

A good example of potentially profound technology impact on "peak oil" is the ongoing transition to electric cars, that would reduce dependence on oil, in the intermediate-term breakthroughs that would make renewable energy, such as solar more competitive, or in the longer-term commercialization of fusion and space power [10,60–63].

A powerful example of the unpredictability and presently uncontrollability of fuel price, is the extreme price fluctuations that are largely unrelated to either supply and demand forces or to the actual cost of the fuel (Fig. 5 and [10,11]). These fluctuations are increasingly understood to be largely controlled by speculation inherent in the world "free" market system, which, in addition, also often gives undue significance to oil as a fuel because it indexes prices of other fuels to that of oil even when they do not compete for the same customers [64]. An example of that is linking gas price to that of oil in the Asian-Pacific markets even though oil is principally used for transportation fuels while gas serves completely different customers such as those engaged in power generation and heating.

The prices not only determine the direct economic impact on customer expenditure preferences and habits but also severely stymie the establishment of competition from other energy sources such as renewable and nuclear.

3.3. The 2008–9 economic downturn as a test on influence on energy use, emissions, and quality of life

The severe economic downturn during 2008 and 2009, which has eased afterwards but is still ominously present, and which was caused by ethically and practically irresponsible greed of financial institutions and customers alike, and allowed by governments, has had also strong effects on energy consumption and related emissions as succinctly shown in Table 2. One way to describe the

Table 2
Some sustainability effects of the global 2008–2009 (2010) economic downturn on the world, the USA, UK, and Serbia.

Region	World average [13,14,40]				USA [12]				UK [1,13,14,65]				Serbia [13,66,67]			
Year/Parameter	2008	2009	2010	2011 (Jan–May)	2008	2009	2010	2011	2008	2009	2010	2011	2008	2009	2010	2011
Total PE consumption, EJ	517.90	506.60			104.67	99.61	103.33		9.43	8.84	9.10		0.66	0.60	0.63	
Energy consumption/person, GJ/person	77.44	74.74			343.90	324.50	333.10		153.79	141.95	145.30		90.04	81.97	86.18	
Electricity generated*, TWh	20,342.00	20,135.50	21,325.10		4,325.40	4,146.60	4,325.90		388.70	375.70	381.20		37.38	38.32	38.34	
Electricity generated/person, kWh/person	3,042	2,971.19	3,095		14,211	13,506	13,944		6,335.78	6,034.37	6,088.48		5.10	5.23	5.24	
Electricity generation capacity, GW	4,711.58				1,010.10	1,025.4 (1,121.7 annual)			83.4	85.30			7.1**	7.1**	7.1**	
Electricity generation capacity, kW/person	0.70				3.30	3.30			1.36	1.37			0.97	0.97	0.97	
Total CO_2 emissions, million ton	30,400.00	30,313.00			5,837.97	5,424.85	5,632.50		525.10	473.70	491.70		51.8***	50.1***		
CO_2 emissions, ton/person	4.54	4.47			19.18	17.67	18.16		8.56	7.61	7.85		7.07***	6.84***		
GDP PPP/person	9,680	9,508	9,869		43,250	41,735	42,551		33,860	31,985	32,173		10,234	9,956	10,174	
Unemployment, %	8.20	8.70	8.80		4.80	8.50	9.70	8.70	5.30	5.60	7.90		14.4	16.90	20.00	22.9
HDI [66]	0.598 (2005)	0.62			0.90	0.90	0.90		0.85	0.85	0.85		0.73	0.73	0.74	
Population, Millions [39]	6,688.00	6,776.92	6,890.65	6,917.41	304.38	307.01	310.23	311.32	61.35	62.26	62.61	62.320	7.33	7.32	7.31	7.31

* Note that electricity consumption was 18,603.00, implying an 8.5% loss. **Data from [67], EIA shows 8.721. ***Data from [13].

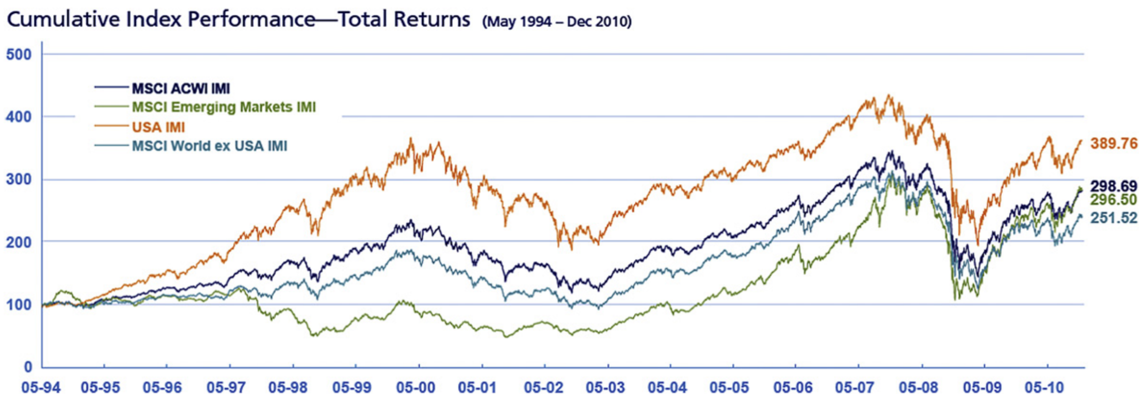

Fig. 7. Stock market comprehensive indices changes with time, the discussion in the paper relates to the MSCI ACWMI IMI (the MSCI All Country World Investable Market Index, contains 45 countries) [36].

downturn is by noting that within 9 months from about June 2008 till March 2009 the MSCI World Index [36] dropped by 45% (Fig. 7). Such an abrupt and major downturn shook the world economy, and alongside it obviously the energy field including consumption, emissions, equipment sales, environmental legislation, and planning.

It is interesting to note the results of this unplanned "experiment". Table 2 shows the changes in a number of important sustainability parameters for the world, the USA as one of the leading energy per-capita-users and emitters, for the UK arbitrarily chosen as a developed country that has a very high standard of living using a much smaller amount of energy per capita than the US, and Serbia, as a developing country and host of the ECOS2011 conference where this paper was the basis of the author's presentation in the World Energy Panel. The parameters are primary energy, electricity, CO_2 emissions, gross domestic product purchasing power party (GDP PPP), the Human Development Index (HDI) that combines indicators of income, education and health into a single index [68], unemployment, and population. Per-capita values are included to shift the focus of development from national income accounting to people-centered policies and to emphasize the importance of individual human responsibility.

While plain examination of raw data trends is not likely to fully capture the nature of the relationship between the global economics and the sustainability and other data shown in Table 2, we nevertheless can draw a few useful conclusions:

- The per-capita energy and electricity consumption, CO_2 emissions, and GDP/PPP have generally exhibited a decline from 2008 to 2009, but have then returned close to the 2008 levels in 2010; the changes for the 2008–2009 period:
  - Energy/person: world −3.5%, USA −5.6%, UK −7.7%, Serbia −9.0%
  - Electricity/person: USA −4.5%, UK −7.1%, Serbia +2.5%.
  - CO_2/person: World −1.5%, USA −7.8%, UK −11.1%, Serbia −2.8%.
  - GDP-PPP/person: World −1.8%, USA −3.5%, UK −5.5%, Serbia −2.7%.
- Notably, the 2008–2009 drop in per-capita CO_2 emissions was in most cases higher than that in energy consumption, partially explained by probable switching to more efficient methods of transportation and energy conversion.
- Unemployment increased everywhere and keeps increasing despite some economic recovery; This can be explained by the fact that employers remain wary of the economic situation, probably for good reason, and because some employment lines were eliminated during the economic downturn and have not been replaced; Unemployment rise during 2008–2010: World 7.3%, USA 102.1%, UK 49.1%, Serbia 38.9%.
- The Human Development Index (HDI) remains unaffected in the developed countries USA and UK, is slightly rising in Serbia and rising even somewhat faster in the World; these observations are explainable by the fact that people in developed countries have more of a personal and governmental welfare cushion that at least temporarily maintains the HDI despite such economic trends, and by the fact that people in developing countries started with a much lower HDI, and because especially in the highly populated China and India the economic downturn was of a somewhat shorter and lesser effect.
- It is also interesting to confirm the weak dependence of HDI on per-capita GDP/PPP and on unemployment rate; e.g.:
  - The USA per capita GDP/PPP (2008–2010 average) is 4.2-fold higher than that in Serbia but its HDI is only 23% higher and in comparison with the UK the USA per capita GDP/PPP is 33% higher but its HDI is only 6% higher.
  - The huge rises in unemployment rate seem to have no effect on HDI, despite the fact that HDI includes income (as Gross National Income, GNI[7] as one of its main metrics; perhaps existing welfare systems supplied adequate income to the unemployed during the economic downturn, or, flippantly, maybe the metrics for health and education improved with unemployment).
  - When considering these facts it is important to keep in mind, however, that while HDI is widely used, especially by the UN, it is certainly not a perfect metric of quality of life [69–71].

The main conclusion from this major economic downturn event used here as a global experiment, is that its biggest impact was on decreasing CO_2 emissions in general but in the developed countries much more significantly, on increasing unemployment that continues despite some economic recovery, and of negligible effect on the quality of life as measured by the HDI. Daring to draw further

[7] Gross National Income (GNI) per capita is defined by UNDP as "the sum of value added by all resident producers in the economy plus any product taxes (less subsidies) not included in the valuation of output plus net receipts of primary income (compensation of employees and property income) from abroad, divided by midyear population. Value added is the net output of an industry after adding up all outputs and subtracting intermediate inputs. When expressed in PPP US dollar terms, it is converted to international dollars using PPP rates. An international dollar has the same purchasing power over GDP that a US dollar has in the U.S.". It thus does not include unemployment level explicitly.

and probably insufficiently-scientific conclusions from this short-term “experiment”, one could see that by significantly turning the economy down, energy consumption, and more significantly CO_2 emissions, will drop, especially in the developed countries, but that would come at the expense of much higher unemployment that, however, seemed to have no effect on HDI.

3.4. The nuclear disaster in Japan and nuclear power future

Past reviews by the author [10,11] have described nuclear power generation statistics, the advantages based on low GHG emissions and fossil fuel independence, but also the remaining unresolved concerns with radioactive waste (especially the long life, dangerous up to a million years) disposition, with mounting proliferation risks, and to some extent with safety, considerations that lead in balance to very slow growth of nuclear power. Since no major nuclear accidents occurred for about 25 years since the massive 1986 disaster in Chernobyl, and since the 104 US reactors operated at a remarkable capacity factor of 91.2% (much higher than those of fossil fuel power plants), safety was increasingly considered to be a relatively low risk problem.

The recent and continuing Fukushima disaster, in which 3 reactors were destroyed by fuel core meltdown, all causing very dangerous radioactive emissions to soil, air and water to very large distances, and that had severe impacts on the Japanese and world economies, caused, justifiably, a major reconsideration of the future of nuclear power. The cleanup is expected to take decades [72]. Some immediate consequences ranged so far from a re-examination of all US and EU nuclear reactors, shelving by Japan of a 2010 goal to build 14 nuclear reactors over the next 20 years [73], and to complete moratoria on nuclear power in Germany and Switzerland.

Much has been written against drastic knee-jerk measures to ban nuclear power, explaining the extremely severe and low probability simultaneous coincidence of a scale 9 earthquake (nuclear plants are designed for much lower earthquake levels) with a 10–15 m high Tsunami, both at the large reactor concentration (6 units in close vicinity) Fukushima Daiichi site, as well as on the weaknesses of these 40-year-old BWR type reactors. Much has also been said about the seeming unpreparedness of the reactor-operating company to such a disaster. There are, however, several fundamental facts that must never be ignored in comparing nuclear to fossil-fuel (or that from renewable energy) power:

A. The energy density of nuclear fission is up to 4 orders of magnitude higher than that of fossil fuels, at the extreme with some remotely probable advent of criticality, making it more complex and risky to control.
B. The radioactive fission products, if released, have a high potential for harm to humans and the environment, and orders of magnitude longer harmful life, than emissions from fossil fuel power plants, and have, justifiably or not, a much larger social and psychological fear factor [73]. A fair part of that fear is due to incomplete scientific understanding of the consequences of nuclear radiation and due to learned distrust of reassurances by both industry and government [74]. Many studies show that coal and hydropower generation result in one to two orders of magnitude higher casualties than nuclear power [75–78] but most of the casualties associated with coal power generation can be reduced very significantly by well established and improving safer mining methods and by emission controls that are commercially available, both at some increase in generated electricity price of course.
C. The large disadvantage of fossil fuel power plants in their effect on global warming can be diminished by higher efficiency, fuel substitution, eventual carbon capture and sequestration, and, very importantly, by demand reduction.

The overall damage and long-term consequences and fear would have been incomparably smaller if these 6 power plants were fossil-fuel fired, or using some types of renewable energy such as solar or wind.

Considering the persistent energy demand growth, practically each energy source is likely to be exploited, including nuclear energy with which about half a century of satisfactory power production was achieved, but to avert the unacceptable risks demonstrated by the Chernobyl and the recent Fukushima accidents it would be wise to wait till a new generation of proven nuclear reactors is available that can withstand extreme natural upheavals, that produce only safe-level short-term manageable radioactive waste, that are proliferation proof, and, practically incredibly, at the same time also produce electricity at a competitive price when considering all externalities. Designing all nuclear power plants to withstand catastrophic freak accidents like Fukushima (or worse) would probably make the power produced uncompetitive, and yet designing them based on some below-certainty risk probability forecast maintains the risk of another major disaster. Designs combining all these desirable features would go beyond the currently planned Generation IV reactors [79,80], and may take more than 50 years to materialize. It is also good to keep in mind that during that long time the competition for power generation would not remain still, and breakthroughs are likely to take place that may postpone nuclear power acceptability.

In addition to technologically reduce risk probability, it is critically important to establish and unfailingly maintain an effective, comprehensive and fast-reacting crisis management system, which also includes forecasting, monitoring and adequate evacuation methods. None of the major nuclear accidents had this in place, and it clearly appears that the communications and coordination between those responsible were, at least at the critical beginning of an accident, woefully bad.

Lastly, a consistent iniquitous trait of all major nuclear accidents, Three Mile Island in the US, Chernobyl in the USSR, and Monju and Fukushima in Japan, is the coverup and outright lies to the public by the plant owners and the authorities. While the justification given by them for such behavior is protection of the public from panic that may significantly increase the accident consequences, it breeds distrust both in those responsible and in the technology. Apparently, a combination of ethics and regulation must be applied to information dissemination in such disasters.

4. An unofficial review of the U.S. administration's energy R&D budgets and trends [81]

While 2009 was an important year for energy in the U.S. because it was the first after the Democrat Party took over from the Republicans (see USDOE budget comments in the author's paper [11]), the USDOE budget request for 2012, the presidential election year, allows some examination of the administration's ongoing goals as adjusted by government experience and pressing competition with other budgetary needs. The latter are dictated to large extent by the highest-ever monumental national debt of \$14,290,788,661,250.50 ($\sim$\$1.43 $\times$ 10^{13}, April 21, 2011 [82]), that rose by 35.2% since the 2008 elections, or 29.7% in 2008 dollars when considering a. 4% total inflation CPI.

In this section I briefly summarize the U.S. Department of Energy (DOE) fiscal year 2012 budget request to the US Congress that pertains to the energy and environment area and discuss changes relative to past years. Such a request is an indicator of the administration's wishes and directions but is subject to Congress approval, which under the current Republican Party majority and national debt circumstances is likely to be significantly reduced. Some of the statements are taken verbatim from the DOE budget documents, but the commentary is entirely the author's and does not represent, nor is sanctioned by, government. The requested budget is stated to support the President's commitment to the challenges of innovation leadership, and to generate 80% of U.S. electricity from clean sources by 2035, reduce dependence on oil, accelerate the transition to a clean energy economy and promote economic competitiveness, and clean up the wastes of the nuclear legacy (continue cleaning up, with no clear end, I add).

The R&D budgets, their changes and some of my clarifications are briefly summarized in Table 3. In addition to these R&D budgets, the FY 2012 budget request includes $300 million in credit subsidies to support approximately $3–4 billion in projects, and $36 billion in loan guarantee authority to help jumpstart the domestic nuclear industry, as well as additional investments in the research and development of advanced nuclear technologies, including small modular reactors. The loan guarantee authority is to support 6–8 nuclear power projects resulting in the construction of anywhere from 9 to 13 new reactors. The nuclear jumpstart budget request was prepared prior to the Fukushima nuclear disaster and is likely to be reduced or redirected to safety assurance of the existing nuclear reactor stock.

$550 million are requested for the Advanced Research Projects Agency-Energy (ARPA-E, [83]) to continue support for the promising early-stage research projects that could deliver what the DOE calls "game-changing" clean energy technologies, and $146 million to support the three existing Energy Innovation Hubs and to establish three new Hubs in the areas of batteries and energy storage; smart grid technologies and systems; and critical materials, and $100 million to continue supporting 46 Energy Frontier Research Centers started in 2009 (also see Ref. [11]).

Originally the new administration proposed to use a cap-and-trade process, planning to reduce the U.S. greenhouse gas emissions by 14% under the 2005 baseline by the year 2020, and by 83% below the 2005 baseline by 2050 (similar to the Intergovernmental Panel on Climate Change (IPCC) proposal). This proposal met strong opposition in Congress and is currently at best in limbo.

The remaining information presented here about the budgets must be prefaced with a statement that examination of governmental and institutional aims and budgets is very difficult, in part because of duplication and overlap of programs, and frequent changes across them, and all the numbers given here are thus not always precise.

Table 3
USDOE budget request changes of some key energy R&D items, from FY2008 to FY2012, in 2008 dollars (~4% total inflation), and from the 2010 appropriation to the 2012 request [81].

Appropriation	FY2008 budget appropriation, thousands $	FY2012 budget request (in thousands 2008 $)	% change 2012/2008, in 2008 $	% change (2012 request)/(2010 appropriation), in the years' $	Comments, focus
Energy efficiency and renewable energy	1,704,112	3,072,051	+80.3	+44.4	Main rise in renewable, efficiency, distribution
Hydrogen and fuel cell technology	206,241	96,432	−53.2	−69.0	Declining
Biomass and biorefinery systems R&D	195,633	326,880	+67.1	+57.5	Cellulosic ethanol
Solar energy	166,320	438,720	+263.8	+87.8	PV, some CSP
Wind energy	49,034	121,785	+248.4	+60.6	Reliability, direct drive, offshore
Geothermal technology	19,307	97,474	+504.9	+135.5	Exploration technologies, strong boost to major resource
Water power	9,654	36,960	+382.8	−20.9	Declining; small hydro, pumped storage
Vehicle technologies	208,359	564,483	+270.9	+93.3	Electric cars
Building technologies	107,382	451,872	+420.8	+114.9	Rising, but same old
Industrial technologies	63,192	306,993	+485.8	+239.2	Manufacturing
Electricity delivery and energy reliability	136,170	228,208	+67.6	+41.1	Recognition of significance
R&D	109,502	185,104	+69.0	+58.8	
Fossil energy R&D	727,181	434,856	−40.2	−44.5	Major declines
Coal	493,382	279,704	−43.3	−26.0	The continuing decline regrettably puts "Clean Coal" at risk
Gas	19,818	0	−100.0	−100.0	Traditionally low investment, but badly timed zeroing in view of discoveries of abundant shale gas
Oil	4,954	0	−100.0	−100.0	
Nuclear energy	960,903	818,427	−14.8	−0.6	Continuing decline, jeopardizing future role
R&D	257,171	216,349	−15.9	−100.0	
Fuel cycle research and facilities	456,806	148,810	−67.4%	+17.5	
Total, Energy	3,761,988	4,618,565	+22.8	+15.1	
Total, Environment	6,332,142	6,048,164	−4.5	−1.5	
Energy Information Administration	95,460	118,999	+24.7	+12.1	EIA is a very valuable resource
Science	4,082,883	5,199,467	+27.3	+9.1	Continuing valuable rise
Advanced Scientific Computing Research	341,774	446,976	+30.8	+21.5	
Basic Energy Sciences	1,252,756	1905,600	+52.1	+24.1	
Biological and Environmental Research	531,063	689,184	+29.8	+22.1	
Fusion Energy Sciences Program	294,933	383,712	+30.1	−4.3	
High Energy Physics	702,845	765,312	+8.9	+0.8	
Nuclear Physics	423,671	581,088	+37.2	+15.9	
ARPA	–	624,011	Did not exist in 2008	No appropriations yet in 2010	Transformational energy technologies

Out of the USDOE energy R&D part, the programs of energy efficiency and renewable energy continues to increase their dominance to 67% (from 58% in 2010, 53% in 2009 and 48% in 2008) relative to those of fossil energy (dropped to 9%), and civilian nuclear energy (dropped to 18%). The only drops in the energy efficiency and renewable energy category are in hydrogen and fuel cell technology, −69%, and water power, −21%.

A few more interesting details are that biomass and biorefinery systems R&D appears to move strongly away from food-to-fuel conversion to cellulosic ethanol, and continuing recognition of the importance of geothermal energy (+135%) and of electricity delivery and energy reliability (transmission, smart grid, etc., +41%).

The severe drop of 44% in fossil fuel energy, including the clean coal program with carbon capture and sequestration should be of great national and global concern because of the abundance of coal and its leading role in power generation in China, India and the US, and its leading contribution to global warming. What can be interpreted as an important public message is that USDOE Secretary Chu's speech and presentation introducing the 2012 budget request [84] does not mention the word coal while it does mention renewable energy and efficiency frequently and mentions nuclear power advancement by an additional $36 billion in loan guarantee authority, and small modular reactors development. It is a big question whether industry can take these coal R&D tasks over, relying only on the commercial potential of associated processes and technologies. Furthermore, the USDOE is also catching up very slowly to the significant R&D needs for the huge shale gas resources recently discovered in the US and available in other countries too.

About nuclear energy, the USDOE states that "the aim of the nuclear program is to enable nuclear energy to be used as a safe, advanced, cost-effective source of reliable energy that will help address climate change by reducing greenhouse gas emissions", with a safety focus on proliferation resistance and on development of advanced reactor designs and technologies, including small-scale standard design modular reactors (<300 MWe, based on LWR principles), but the budget was slightly reduced. All funding for development of the Yucca Mountain facility for a permanent geologic storage site for spent nuclear fuel and high-level radioactive waste nuclear waste has been eliminated already in 2009 (after the US spent about $13.5 billion (2007 value) over the 26 years of the project). The absence of prospects for availability of such a facility is a significant blow to global nuclear power development since the world has no alternate methods for storing the growing amount of long-lived radioactive waste, especially that generated by nuclear power generation. A Blue-Ribbon Commission was established and charged with providing recommendations about long-term nuclear waste storage, and their first report to President Obama is due in July 2011.

The DOE's Science programs (nuclear physics including major facilities, materials, nanoscience, hydrogen, advanced computing) budgets were significantly increased, by 9.1%, with the only decrease being in the nuclear fusion program (−4.1).

Based in large part on the USDOE budget trends, Table 4 very qualitatively summarizes the author's view of the promise and potential of the major energy R&D areas, foreseen improvements and their time scale, and trends in the U.S. government funding.

A very important observation that needs re-emphasis is that while the overall USDOE energy budget is raised by only a few percent each year, it is remarkable that it even holds its own in view of the staggering US national deficit, which also explains why the significant increases in allocations to renewables and energy conservation are associated with commensurate significant reductions in fossil energy development.

While the USDOE oversees most of the moneys related to energy, there are some additional but smaller amounts within other government domains such as the Environmental Protection Agency (EPA), Department of Transportation, Department of Housing and Urban Development, the National Science Foundation, and the National Aeronautics and Space Administration (NASA, its overall budget request for 2012 is 18.7 billion dollars, significantly higher than that of the energy-related USDOE one).

An educational endnote to the US energy budget discussion is that environmentally unsustainable 60 years of nuclear weapons production and government-sponsored nuclear energy research resulted in a long-term annual management and remediation ("cleanup of the environmental legacy") expenditure that is now at 6.3 billion dollars a year (with no sign of ending any time soon), larger than the entire annual "Energy and Environment" R&D budget of 4.8 billion dollars, and separately of the energy science R&D program netting specifically for energy about 5 billion dollars. It consummately demonstrates how past unsustainable activities penalize progress to the future.

5. Possibly sustainable paths to the future

- The last few years have introduced three game-changers in the very dynamic energy field: the apparent postponement of the threat of depletion of fossil fuels, new realization of the strong impact of economics on energy use and related emissions that arose from the recent global economy downturn, and the realization of the vulnerability of nuclear power as exhibited by the recent tragic nuclear disaster in Japan. These have, or should have, major consequences for sustainable development as discussed in somewhat more detail below and in some other parts of this paper.
- The first step in any path to the future is wiser use of the energy resources, also referred-to as conservation (nicely reminded by Smil [85]). This would include elimination of obvious waste, higher energy conversion efficiency, substitution for lower energy intensity products and processes, recycling, and more energy-modest lifestyles. Conservation must be implemented in a way that does not deprive people from the basic necessities and comforts of life, nor has a very negative impact on productivity. Considering that the per capita energy consumption in some leading energy consumers is much higher than the world average, e.g. ~3.4-fold higher for the USA, and importantly, for the USA more than two-fold higher than that in developed countries of similar quality of life, it is clear that ways can be found to reduce the demand significantly without undue stress on life quality. There is even the clear prospect that reduction of such extravagant energy consumption may improve the quality of life. Such demand reductions have significant potential for numerous countries, including many of the developing ones that actually have an excellent chance to learn from the unsustainable paths taken in the past by the developed ones and to incorporate sustainability during their development, all this leading to a more sustainable world.
- Important steps must also be taken to prevent energy efficiency "rebound", the frequent outcome in which higher efficiency and lower costs lead to increased consumption (cf. [86,87]).
- It is impossible to find and implement effective ways for curbing energy demand and related emissions, and for supplying the needed energy, if the wide fluctuations in oil and gas prices, like those experienced in the course of the past year, are not curbed. Apart from inadequately regulated speculation, parts of that problem are the market practices of linking/

Table 4
Author's qualitative assessment of promising research directions and their U.S. government funding trend (based on the proposed 2012 annual budget).

Direction	Potential	Foreseen improvement	Time scale, years	2012 Government funding trend
Conservation	☆☆☆+	50% reduction of use	Ongoing	☺☺
Buildings energy	☆	20% reduction by 2020	8?	☺☺
Transportation	☆☆☆+	50% of use; 120 g CO_2/km by 2012; 1 million electric cars by 2015*	3–20	☺☺
Hydro power	☆	Small hydro, pumped storage, reduction of environmental harm	Ongoing	☹☹☹
Biomass	☆☆+	30% U.S. energy; cellulosic ethanol at $2.76/GGE* in 2012	4–40	☹
Wind	☆☆☆	2.5 c/kWh, 15% of electricity	1–6	☺☺
Solar PY	☆☆☆+	Competitive price: $1/WDC, 4–5 c/kWh	8+	☺☺
Solar thermal	☆☆☆	Competitive price: 4–5 c/kWh	8+	☺
Geothermal (deep)	☆☆	Expand resource: exploration and deep drilling	20	☺
Hydrogen	☆☆	Affordable transport fuel	15	☹☹
Fossil fuel power	☆☆	67–75% efficiency, ~0 emission	6–15	☹☹
Oil and Gas	☆+	Exploration, recovery, transportation	3–15	☹☹☹
Coal	☆+	Exploration, recovery, transportation, conversion	8	☹☹
Energy storage	☆☆☆+	Cost, weight and volume reduction	5–12	☺
Electricity transmission	☆☆☆	Grid expansion, smart grid, loss reduction	10	☺☺
Global warming	☆☆	0 CO_2	10–15	☺
Fuel cells	☆+	60% + efficiency; order of magnitude price reduction, 6 kW/g Pt-type catalyst in 2012	7	☹☹
Micropower	☆☆☆	Cost, market penetration	7+	☺
Superconductivity	☆☆☆	Order of magnitude	30+	☹☹
Nuclear fission	☆	Manageable wastes, no proliferation, safety: Gen IV, thorough review	10	☹
Nuclear fusion	☆☆☆	Feasibility	35+	☺
Space power	☆☆☆+?	Competitiveness	50+	☹☹☹

*The US has about 260 million highway vehicles. **GGE Gallon Gasoline Equivalent. ☺: Increased; ☹: decreased.

indexing the prices of noncompeting fuels, such as oil and gas, in several major areas of the world [64]. These fluctuations could be diminished by a combination of technical measures and fiscal regulation, and should be implemented rapidly.

- Much more effective involvement of, and cooperation among, the countries of the world in reducing GHG emissions and other negative environmental consequence of energy use must be more rapidly put into action. Respecting the need of developing countries for more complete and rapid electrification and better transportation, the needed methodology and technology must be aided by developing countries to the benefit of both and of the world in general.
- Since large-scale carbon sequestration is still impractical, proper credit should be given to maintenance and increase of carbon consuming forest and other green areas, and major research, development and testing must be performed on carbon sequestration as well as on increased use of appropriate renewable energy.
- The pursuit of more efficient and less polluting transportation must include not only vehicular improvements (with

preference for the plug-in electric or hybrid car) but also traffic management, significant development of efficient public transit, and redesign of cities [10].

- Buildings are the biggest single contributor to world greenhouse gas emissions, and it is generally felt that one of the most effective ways to reduce this problem is through market drivers, by legislation that assigns real costs to building energy use and emissions, accompanied by financing practices that monetize long-term energy costs in near-term investment decisions (for more about buildings energy see Ref. [10]). Governments make huge investments in subsidizing energy-efficient buildings and their use, but this is a very ineffective method without generating the above mentioned market drivers.
- At least for this century, during which massive use of fossil fuel is likely to continue, more efficient and less polluting use of fossil fuels, as well as better and cleaner exploration and extraction of such fuels, is to continue to be pursued. Since coal is and will remain in the foreseeable future to be the major fuel for electricity generation, development of clean use of coal should be accelerated. Environmentally acceptable ways of making use of the vast oil sands, shale gas, and perhaps even shale oil, must be developed before they are massively used.
- It appears that massive use of nuclear fission power would be stymied until the reactors are deemed or developed to be safe enough, with permanent and economical solutions to the nuclear waste problem. Nuclear fusion power could produce a very satisfactory long-term solution, but the R&D is underfunded and unstable, and commercial use is still rather far from achievement.
- R&D and implementation of renewable energy must continue vigorously, with the most promising technologies currently being wind, solar photovoltaics and solar thermal power, and to some extent biomass that does not compete with food. Economical very deep drilling technologies for reaching the enormous renewable geothermal heat resources should be pursued.
- The inequitable costing of energy resources and their conversion must stop, by governments and industry assigning a true value based on all short- and long-term externalities. In-depth scenario studies are necessary for quantitative forecasting of the best ways to spend government research moneys for attaining the sustainable development objectives.
- It is not conceivable that sustainable development can take place without applying reasonable measures for population control.
- As I wrote in several past papers, sustainability is only emerging as a science, and must be developed and applied urgently to provide analysis and evaluation tools. It is of immediate importance because energy conversion and use are associated with major environmental, economical and social impacts, and all large energy projects should therefore be designed and implemented sustainably.
- The critical problems that energy development poses and the possible paths to the future create at the same time great opportunities for respected solutions by the engineering/scientific community that promote new and expanded creativity, higher employment, and higher job satisfaction. They also offers special prospects for small enterprises and nations that are not hampered by the inertia inherent in larger organizations.
- A frequent major obstacle is the political system needed to support rapid and effective movement along the new paths, and to plan beyond its tenure, and that often prefers solutions that are primarily supportive of its own survival: popular support for sensible paths should be sought/educated to diminish this obstacle.
- Many of the innovative solutions require very long periods of time. It is of vital importance to start intensively now, so we wouldn't be too late.

Acknowledgment

The help of Professor Petar Škundrić and Ms. Maja Krunić-Lazić in pointing me to sources of some of the data shown in Table 2 for Serbia is gratefully acknowledged.

References

[1] British petroleum. Statistical review of world energy, June 2011, http://www.bp.com/liveassets/bp_internet/globalbp/globalbp_uk_english/reports_and_publications/statistical_energy_review_2011/STAGING/local_assets/pdf/statistical_review_of_world_energy_full_report_2011.pdfandElectricity; June 2011, http://www.bp.com/sectiongenericarticle800.do?categoryId=9037156&contentId=7068663; June 2011 [accessed 15.06.11].

[2] British petroleum energy outlook 2030, http://www.bp.com/liveassets/bp_internet/globalbp/globalbp_uk_english/reports_and_publications/statistical_energy_review_2011/STAGING/local_assets/pdf/2030_energy_outlook_booklet.pdf; 2011 [accessed 15.06.11].

[3] U.S.D.O.E. http://www.energy.gov/ [accessed 15.06.11].

[4] U.S.D.O.E. Energy Information Administration http://www.eia.doe.gov/ [accessed 15.06.11].

[5] International Energy Agency. http://www.iea.org/ [accessed 15.06.11].

[6] International Atomic Energy Agency. http://www.iaea.org/ and http://www.iaea.org/programmes/a2/index.html [accessed 15.06.11].

[7] Lior N. The state and perspectives of research in the energy field, invited keynote paper. In: Ulgiati S, editor. The third international biennial workshop "Advances in energy studies: reconsidering the importance of energy" Porto Venere, Italy, 24–28 September 2002, p. 351–364.

[8] Lior N. Energy resources and use: the present situation and possible paths to the future. In: Invited Keynote Lecture, PRES 06 (9th Conference "Process integration, modeling and optimisation for energy saving and pollution reduction"), joint with CHISA 2006 (17th international congress of chemical and process engineering), Praha, Czech Republic, August 2006; in revised form in Energy, vol. 33; 2008. p. 842–57.

[9] Lior N. Energy resources and use: the present situation and possible sustainable paths to the future. In: invited keynote presentation at SET 2008, the 7th Conference on Sustainable Energy Technologies, Seoul, Korea, 24–27 August 2008. Proc. ISBN:978-89-961095-1-894540. vol. 1. p. 55–67, published by Korea Institute of Ecological Architecture and Environment, Seoul, Korea. In revised form: Lior, N. Energy resources and use: the present (2008) situation and possible sustainable paths to the future, Energy 35(2010) 2631–2638.

[10] Lior N. Sustainable energy development: the present (2009) situation and possible paths to the future. Energy 2010;35:3976–94.

[11] Lior N. The ECOS 2009 World Energy PF.N, anel: an introduction to the Panel and to the present (2009) situation in sustainable energy development. Energy 2011;36:3620–8.

[12] U.S.D.O.E. Energy information administration – Annual energy outlook 2011. http://www.eia.gov/forecasts/aeo/ [accessed 15.06.11].

[13] IEA. Key world energy statistics, http://www.iea.org/textbase/nppdf/free/2010/key_stats_2010.pdf; 2010 [accessed 15.06.11].

[14] IEA. World energy outlook 2010. Paris; 2010 [accessed 15.06.11].

[15] W.H.O. and U.N.E.P. Intergovernmental panel on climate change. Geneva, Switzerland: http://www.ipcc.ch/ [accessed 15.06.11]

[16] National Oceanic and Atmospheric Administration, National Climatic Data Center. State of the climate, global analysis, http://www.ncdc.noaa.gov/sotc/global/; May 2011 [accessed 15.06.11].

[17] UNICEF and World Health Organization. Progress in water and sanitation, http://www.unicef.org/wash/; 2008 [accessed 15.06.11].

[18] Lior N, Bakish R. Water, supply and desalination, chapter in the Kirk-Othmer encyclopedia of chemical technology. 4th ed., vol. 25. John Wiley and Sons, Inc.; 1998. p. 438–487.

[19] UN World Food Programme. Hunger, Rome, Italy http://www.wfp.org/hunger [accessed 15.06.11].

[20] Weil RH. Levels of overweight on the rise. Worldwatch Institute, http://vitalsigns.worldwatch.org/vs-trend/levels-overweight-rise; Jun 14, 2011 [accessed 15.06.11].

[21] ENERDATA. World energy use in 2010, over 5% growth, http://www.enerdata.net/; May 5, 2011 [accessed 15.06.11].

[22] Ewing RC, von Hippel FN. Nuclear waste management in the United States — Starting over. Science 10 July 2009;325:151–2.

[23] USDOE Blue Ribbon Commission on America's Nuclear Future. What we have heard, www.brc.gov; March 2011 [accessed 15.06.11].

[24] Toleffson J. Battle of Yucca Mountain rages on. Nature 19 May 2011;473:266.

[25] Trainer T. Renewable energy cannot sustain a consumer society. AA Dordrecht: Springer; 2007.

[26] Turney D, Fthenakis V. Environmental impacts from the installation and operation of large-scale solar power plants. Renew Sustain Energy Rev 2011;15:3261–70.

[27] MIT Panel. The future of geothermal energy. Cambridge, MA: Massachusetts Institute of Technology, http://geothermal.inel.gov/publications/future_of_geothermal_energy.pdf; 2006 [accessed 15.06.11].
[28] Electrification Coalition Electrification Roadmap.. Revolutionizing transportation and achieving energy security. Electrification Coalition 1111 19th street, NW suite 406 Washington, DC 20036 Tel 202-461-2360 Fax 202-461-2379, ElectrificationCoalition.org; November 2009.
[29] Sundset T, de Koeijer G. Future power generation in oil and gas industry. In: Lior N, editor. Brief summary of the ECOS '05 panel on future power generation. Energy, vol. 32; 2007. p. 255–6.
[30] Ehlig-Economides C, Economides MJ. Sequestering carbon dioxide in a closed underground volume. J Petrol Sci Eng 2010;70:123–30.
[31] USDOE Nuclear Energy. Small modular reactors www.nuclear.energy.gov/pdfFiles/factSheets/2012_SMR_Factsheet_final.pdf 2/11/2011 [accessed 15.06.11].
[32] Amin SM, Gellings CW. The North American power delivery system: balancing market restructuring and environmental economics with infrastructure security. Energy 2006;31:967–99.
[33] IPCC SRREN. Summary for policy makers, http://srren.ipcc-wg3.de/report; May 31st 2011 [accessed 15.06.11].
[34] UNESCO and Earthscan. The United Nations world water development report 3: water in a changing world. Paris: UNESCO, and London: Earthscan, http://www.unesco.org/water/wwap/wwdr/wwdr3/pdf/WWDR3_Water_in_a_Changing_World.pdf; 2009 [accessed 17.09.11].
[35] WWF (World Wildlife Federation; World Wide Fund For Nature). Living planet report, http://www.panda.org/about_our_earth/all_publications/living_planet_report/2010_lpr/; 2010.
[36] MSCI Index ACWMI IMI. http://www.msci.com/ [accessed 15.06.11].
[37] Index Mundi. http://www.indexmundi.com/g/g.aspx?c=xx&v=67 [accessed 05.08.11].
[38] IEA. World energy outlook 2009. Paris; 2009.
[39] U.S. Census Bureau, International Data Base (IDB). World population: 1950–2050. Update, http://www.census.gov/ipc/www/idb/worldpopgraph.php; December 2010 [accessed 15.06.11].
[40] The World Bank. Energy use per capita. http://data.worldbank.org/indicator/EG.USE.PCAP.KG.OE [accessed 15.06.11].
[41] IPCC. 16 years of scientific assessment in support of the climate convention, www.ipcc.ch/pdf/10th-anniversary/anniversary-brochure.pdf; December 2004 [accessed 15.06.11].
[42] Weart SR. The discovery of global warming. Cambridge, MA: Harvard University Press; 2008.
[43] Energy Resource Potential of Methane Hydrate US DOE methane hydrate primer, http://www.netl.doe.gov/technologies/oil-gas/publications/Hydrates/2011Reports/MH_Primer2011.pdf; 2011 [accessed 15.06.11].
[44] Government of Alberta. Energy http://www.energy.gov.ab.ca/OilSands/oilsands.asp [accessed 15.06.11].
[45] USDOE Office of Naval Petroleum and Oil Shale Reserves. National strategic unconventional resources model instruction manual, http://fossil.energy.gov/programs/reserves/npr/NSURM_Documentation.pdf; April 2006 [accessed 15.06.11].
[46] Shell. Report on Royal Dutch Shell plc & oil sands, http://www-static.shell.com/static/investor/downloads/news_and_library/report_royaldutchshell_oil_sands_march2010.pdf; March 2010 [accessed 15.06.11].
[47] Sawyer D, Stiebert S, EnviroEconomics Inc.. Fossil fuels – At what cost? Government support for upstream oil activities in three Canadian provinces: Alberta, Saskatchewan, and Newfoundland and Labrador. Geneva, Switzerland: The Global Subsidies Initiative (GSI) of the International Institute for Sustainable Development (IISD), http://www.globalsubsidies.org/files/assets/ffs_awc_3canprovinces.pdf; November 2010 [accessed 15.06.11].
[48] Harper JA. The Marcellus Shale — An old "New" gas reservoir in Pennsylvania. Pennsylvania Geol Spring 2008;38(1).
[49] U.S. Department of Energy, Office of Fossil Energy and National Energy Technology Laboratory. Modern shale gas development in the United States: a primer. Prepared by Ground Water Protection Council, Oklahoma City, OK 73142 and ALL Consulting, Tulsa, OK. 74119, http://www.netl.doe.gov/technologies/oil-gas/publications/epreports/shale_gas_primer_2009.pdf; April 2009 [accessed 15.06.11].
[50] Osborn SG, Vengosh A, Warner NR, Jackson RB. Methane contamination of drinking water accompanying gas-well drilling and hydraulic fracturing. Proc Nat Acad Sci May 17, 2011;108(20):8172–6.
[51] Zoback M, Kitasei S, Copithorne B. Addressing the environmental risks from shale gas development. In: Briefing paper, vol. 1. Worldwatch Institute, http://www.worldwatch.org/files/pdf/Hydraulic%20Fracturing%20Paper.pdf; July 2010 [accessed 15.06.11].
[52] EIA. World shale gas resources: an initial assessment of 14 regions outside the United States. Release date, http://www.eia.gov/analysis/studies/worldshalegas/pdf/fullreport.pdf; April 5, 2011 [accessed 15.06.11].
[53] USDOE. Oil shale and other unconventional fuels activities. http://fossil.energy.gov/programs/reserves/npr/npr_oil_shale_program.html [accessed 15.06.11].
[54] Bunger JJ, Crawford PM, Johnson HR. Is oil shale America's answer to peak-oil challenge? Oil&Gas J; August 9, 2004.
[55] Johnson HR, Crawford PM, Bunger JW. Strategic significance of America's oil shale resource. Prepared for U.S. Department of Energy, Office of the Naval Petroleum and Oil Shale Reserves (DOE/NPOSR). In: Assessment of Strategic Issues, vol. I; March 2004, http://fossil.energy.gov/programs/reserves/npr/publications/npr_strategic_significancev1.pdf; March 2004 [accessed 15.06.11].
[56] Johnson HR, Crawford PM, Bunger JW. Strategic significance of America's oil shale resource. Prepared for U.S. Department of Energy, Office of the Naval Petroleum and Oil Shale Reserves (DOE/NPOSR). In: Oil shale resources – Technology and economics, vol. II; March 2004, http://fossil.energy.gov/programs/reserves/npr/publications/npr_strategic_significancev2.pdf; March 2004 [accessed 15.06.11].
[57] Bartis JT, LaTourrette T, Dixon L, Peterson DJ, Cecchine G. Oil shale development in the United States: prospects and policy issues. RAND Infrastructure, Safety, and Environment (ISE), a division of the RAND Corporation, prepared for the National Energy Technology Laboratory of the U.S. Department of Energy, www.rand.org/pubs/monographs/2005/RAND_MG414.sum.pdf; 2005 [accessed 15.06.11].
[58] Cleveland CJ, Costanza R, Hall CAS, Kaufmann R. Energy and the U.S. economy: a biophysical perspective. Science 1984;225(4665):890–7.
[59] Shell Frontier Oil and Gas Inc.. Plan of operations, oil shale test project for bureau of land management, http://www.blm.gov/pgdata/etc/medialib/blm/co/field_offices/white_river_field/oil_shale.Par.79837.File.dat/OSTPlanofOperations.pdf; February 15, 2006 [accessed 15.06.11].
[60] Glaser PE, Davidson FP, Csigi KI, editors. Solar power satellites, the emerging energy option. New York: Ellis Horwood; 1993.
[61] Lior N. Power from space. Energy Convers Manag J 2001;42(15–17):1769–805.
[62] Mankins JC. Space solar power: a major new energy option? J Aerosp Eng 2001;14(2):38–45.
[63] Zidanšek A, Ambrožič M, Milfelner M, Blinc R, Lior N. Solar orbital power: sustainability analysis. Energy 2011;36:1986–95.
[64] Stern J, editor. Natural gas in Asia: the challenges of growth in China, India, Japan, and Korea. Oxford, UK: Oxford Institute For Energy Studies; 2008.
[65] Department of Energy and Climate Change Statistical Release. UK climate change sustainable development indicator: 2010 greenhouse gas emissions, provisional figures and 2009 greenhouse gas emissions, final figures by fuel type and end-user, http://www.decc.gov.uk/media/viewfile.ashx?filetype=4&filepath=Statistics/climate_change/1515-statrelease-ghg-emissions-31032011.pdf&minwidth=true; 31 March 2011 [accessed 15.06.11].
[66] Statistical Office of the Republic of Serbia. http://webrzs.stat.gov.rs/WebSite/; Ministry of Infrastructure and Energy, Republic of Serbia, http://www.mi.gov.rs/; Ministry of finance, Republic of Serbia http://www.mfin.gov.rs/ [accessed 31.08.11].
[67] Serbian Ministry of Environment, Mining and Spatial Planning Environmental Protection Agency (Maja Krunić-Lazić). "Report on the state of environment in the Republic of Serbia for 2009" and "Draft Report on the state of environment in the Republic of Serbia for 2010"; Some data also available in accessed 17.08.11.
[68] UNDP. Human development indices: statistical update. United Nations Development Program, http://hdr.undp.org/en/media/HDI_2008_EN_Complete.pdf; 2008 [accessed 15.06.11].
[69] Sagar Ambuj D, Najam Adil. The human development index: a critical review. Ecol Econ 1998;25(3):249–64.
[70] Neumayer Eric. The human development index and sustainability – A constructive proposal. Ecol Econ 2001;39:101–14.
[71] Wilson J, Tyedmers P, Pelot R. Contrasting and comparing sustainable development indicator metrics. Ecol Indicators 2006;7:299–314.
[72] Cyranoski D. Japan rethinks its energy policy. Nature 19 May 2011;473(11):263.
[73] Smith J. A long shadow over Fukushima. Nature April 2011;472(77):7.
[74] von Hippel FN, Brenner DJ, Lyman ES, Chapin DM, Cohen KP, Davis WK, et al. Revisiting nuclear power plant safety. Science, New Series Jan. 10, 2003; 299(5604):201–3.
[75] Levenson M, Rahn F. Realistic estimates of the consequences of nuclear accidents. Nucl Technol 1981;53:99–110. ANS, May 1981.
[76] Chapin DM, Cohen KP, Davis WK, Kintner EE, Koch LJ, Landis JW, et al. Nuclear power plants and their fuel as terrorist targets. Science September 2002; 297(20):1997–9.
[77] Pennington CW. Exposing America: comparative assessments of ionizing radiation doses to U.S. populations from nuclear and non-nuclear industries. Prog Nucl Energy 2007;49:473–85.
[78] OECD Nuclear Energy Agency. Comparing nuclear accident risks with those from other energy sources. NEA No. 6861, http://www.oecd-nea.org/ndd/reports/2010/nea6862-comparing-risks.pdf; 2010 [accessed 15.06.11].
[79] US DOE. Gen IV nuclear energy systems. http://www.ne.doe.gov/genIV/neGenIV1_demo.html [accessed 15.06.11].
[80] Lake JA. The fourth generation of nuclear power. Prog Nucl Energy 2002; 40(3):301–7.
[81] USDOE. FY 2012 DOE budget request to congress. http://www.cfo.doe.gov/budget/12budget/Content/FY2012Highlights.pdf [accessed 15.06.11].
[82] U.S. Department of Treasury. Debt to the Penny and who holds it. http://www.treasurydirect.gov/NP/BPDLogin?application=np [accessed 15.06.11].
[83] USDOE ARPA-E. http://arpa-e.energy.gov/Home.aspx [accessed 15.06.11].
[84] Simmons G. Secretary Chu hosts FY 2012 budget briefing, http://blog.energy.gov/blog/2011/02/14/watch-live-130-secretary-chu-hosts-fy-2012-budget-briefing; February 14, 2011 [accessed 15.06.11].
[85] Smil V. Global energy: the latest infatuations. Am Sci 2011 May–June;99:212–9.
[86] Herring H. Energy efficiency — A critical view. Energy 2006;31:10–20.
[87] Sorrell S, Dimitropoulos J. The rebound effect: microeconomic definitions, limitations and extensions. Ecol Econ 2008;65:636–49.