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Sustainable energy development: The present (2009) situation and possible paths to the future☆

Noam Lior*

Department of Mechanical Engineering and Applied Mechanics, University of Pennsylvania, Philadelphia, PA 19104-6315, USA

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ABSTRACT

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 (including hydrogen, fuel cells, micropower systems, and the futuristic concept of generating power in space for terrestrial use), is presented. Comments about energy use in general, with more detailed focus on insufficiently considered areas of transportation and buildings 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 government funding are presented.

1. An executive summary of the paper

The status at the end of 2008 of energy resources and use, emissions, and related areas of water and agricultural food production, is briefly summarized. Elaboration follows in Sections 2–5, discussion of R&D funding in Section 6, and recommendations for possible paths to the future in Section 7.

The current energy resources and consumption situation has not changed much relative to last year:

- ➢ A major concern (or opportunity?) is, however: the price of oil was lately 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, but then precipitously dropping to \$40 by the end of 2008.

The peak price is 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.

- ➢ In 2008 world primary energy use rose by 1.4%, with the increase *rate* dropping, due to rising prices, the recent economic downturn, and increases in energy efficiency, but is likely to rise again soon with the economy, as the large developing countries in Asia keep improving their standard of living, China's rose by 7.2% (lowest since 2002), India's by 5.6%, and some significant drops are those of the EU − 0.56%, Japan − 1.9%, US − 2.8%, and led by Australia − 4.2%.
- ➢ The reserves-to-production ratio (R/P) remains rather constant: ~40 for oil, ~60 for gas, and 120+ for coal, and mostly rising! 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.
- ➢ Nuclear power produces ~14% of world electricity; the number of reactors is increasing very slightly; public perception is improving, new government initiatives started, but the same problems remain. Recent stoppage of the development of the Yucca Mountain long-term nuclear waste storage facility is a serious setback.
- ➢ Renewable energy can satisfy at least two orders of magnitude more than the world energy demand, but negative impacts are not inconsequential (Section 4.5 below).
  - ○ Wind and solar photovoltaics (PV) are experiencing an exponential growth as costs decrease.

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* Tel.: +1215 8984803; fax: +1 215 5736334.
E-mail address: lior@seas.upenn.edu

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- ○ Interest is renewed in solar-thermal power.
- ○ Geothermal energy deserves more attention.
- ➢ Strong subsidies for converting food to fuel are increasingly proven to be a mistake, the price of foods has risen and their availability reduced, and are raising water consumption, all as predicted by some ahead of time.
- ➢ While hydrogen and fuel cells continue to be valuable in the energy portfolio, they have not met the expectations expressed by the huge R&D investments made by many governments. This could have been foreseen by more careful early analysis, and some of the moneys and valuable scientists' time could have been spent better.
- ➢ 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 do not receive adequate attention.
- ➢ The new U.S. administration's requested annual energy budget:
- ○ Somewhat favours renewable energy development and global warming control.
- ○ Is slightly lower than last year's.
- ○ But received a one-time order of magnitude increase through the economic stimulus program intended to ease the unexpected economy turndown.
- ➢ Globally, costing of energy resources remains inequitable, as it does not include subsidies, environmental impact, and other consequences.
- ➢ Development of renewable energy, and of all energy systems for that matter, is dominated by the highly controlled, cost-unrelated, highly fluctuating and unpredictable conventional energy prices.
- ➢ Fuel and energy consumption in general must be significantly constrained, with due attention to prevention of the rebound effects; Pursuit of higher efficiency without care of the rebound effect is counterproductive.
- ➢ The "Living Planet Index" is estimated to have declined since 1970 by about 30%, and the "Ecological Footprint" increased by 70% in the same period: we seem to be *running out of environment much faster than out of resources*.
- ➢ *It is highly inadvisable, and unlikely, that energy resourcing, conversion and consumption continue to be developed unsustainably*.
- ➢ Sustainability is only emerging as a science, and must be developed and applied urgently.

1.1. Future power generation

- ➢ The 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 3.5 days.
- ○ E.g., China is adding already one coal-fired 1000 MW plant each week.
- ➢ The global electric energy generated growth in 2008 was 1.3%, to 20,202 Terawatt-hours = 73.2 EJ.
- ○ The global growth was more than 3-fold lower than in preceding years.
- ○ It dropped in the US by 1.3%, and in the EU by 0.1%, rose in India by 2.9%, China 4.5%.
- ➢ 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 demand for electricity in a most significant way, perhaps doubling it.
- ➢ To mitigate associated negative effects of such massive increase, it would increasingly have to be done sustainably.
- ➢ Because of its abundance in the most energy consuming countries such as China, the USA, parts of Europe, India, and Australia, coal is likely to be increasingly the main basic fuel for power plants, partially after conversion to gaseous or even liquid fuels, with the reduced emissions IGCC (Integrated gasification combined cycle) plant receiving major attention.
- ➢ The combined cycle 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 technology for CO_2 capture in fossil fuel power generation is within reach, but sequestration of the CO_2 is not yet
- ➢ Despite the unresolved problems of waste storage, proliferation risk, and to some extent safety, nuclear power plants are likely to be constructed at least for special needs, such as countries that have much better access to uranium than to fossil fuels, and if carbon emissions become costly. The amount of uranium-235 in the world is insufficient for massive long-term deployment of nuclear power generation, which can change if breeder reactors are used, but that technology is not safe and mature enough and is not likely to be in the next couple of decades.
- ➢ 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 is being employed in many niche applications, but being three to five times more expensive now 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 deserves much more attention.
- ➢ Improvements and technological advances in the distribution and storage of electric power will continue and should be advanced much faster.
- ➢ The investments in energy R&D appear to be much too low, less than half a percent of the monetary value of the energy use, to meet the future needs.

2. Introduction

This paper is a brief summary of the state of current energy resources and use, of their limitations and consequences, and of possible sustainable paths to the future, including energy research funding trends, especially in the U.S. The data are taken from many sources, including the latest energy statistics annual report of British Petroleum (BP) for 2008 [1],[1] the excellent web sites of the U.S. Department of Energy (USDOE) [2], its Energy Information Administration [3], Office of Budget [4], Office of Energy Conservation and Renewable Energy [5], Office of Fossil Energy [6] and the National Renewable Energy Laboratory [7], from the Energy Research web site of the EU [8],

[1] While British Petroleum (BP) has published the Annual Statistical Review of World Energy for 58 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.

the International Energy Agency [9], and the International Atomic Energy Agency [10]. 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 for the situation in 2002 [11], 2006 [12], and 2008 [13] to update the information about this very dynamic field.

Some of the related key global data are shown in Table 1.

A sharp decline in energy research experienced during the 1980s has been somewhat arrested toward the end of the 1990s, primarily due to increasing concerns about global warming from energy-related combustion. This has invigorated R&D in efficiency improvement (including hydrogen, fuel cells, and biomass ethanol), use of energy sources that do not produce CO_2, and in methods for CO_2 capture and sequestration. The interest in energy has received another important boost in the last few years, driven by the exponentially rising energy consumption by the highly populated countries of China and India, accompanied by the heightening tensions with many of the oil and gas producing countries, all of which abetted concerns about energy security. Interest in the energy issue and support for energy R&D are now rising rapidly, inspired by the plans and activities of the European Union, and mostly recently by the election of a new administration in the U.S. that promises to take a much more effective action on energy and environment. The European Union and Japan appear at present to have and afford the most forward-looking and extensive programs, probably partially because they have a more pressing need for energy than some other countries, they have the economic resources, and don't have to bear the enormous relatively recent defense expenses that the U.S. does.

The recent worldwide economic downturn casts a worrisome shadow on the actual willingness and ability of governments and citizens to make the necessary investments in energy and environment but it also has a silver lining: the U.S. and other countries are making immediate large investments this year to stimulate the economy and create jobs. For example, the portion of the U.S. economic stimulus program dedicate this year to the energy and environment areas is more than 6-fold larger than the typical USDOE annual budget for the same.

Table 1
Some key data during the period 2006–2008.

Item	Global amount
Total primary energy use	473 EJ [1][a]
Industry	19% [14]
Transportation	19% [14]
Residential, services, agriculture	24% [14]
Electricity	38% [14]
Electric power installed	4.4 TWe [14]
Electricity generated per year	20.2 PWh = 73.2 EJ[b] [3,14]
People without electricity	1.9 billion
Global temperature rise in industrial period	0.76 °C, exponential rise[c] [14,15]
Water shortages	900 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 [16,17]
Food shortages	1.02 Billion undernourished people (1 in 6) [18]

[a] 4% lower than the IEA [14] value.
[b] Indicates a 53% power plant capacity factor.
[c] The temperature increase per decade is more than twice as fast as that observed over the preceding hundred years.

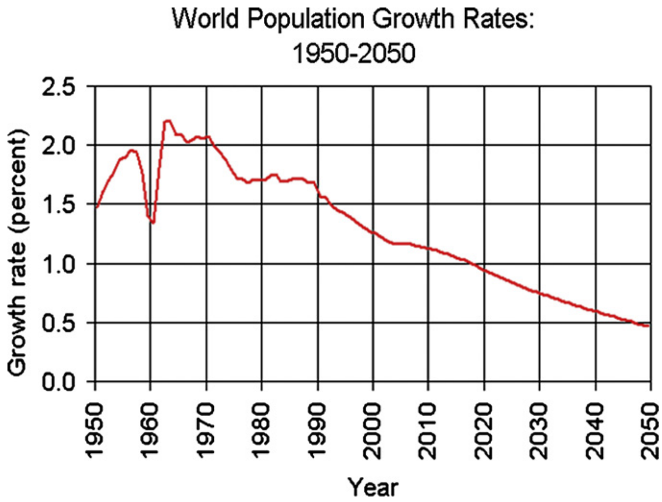

Fig. 1. World population growth rates 1950–2050 [23].

3. Sustainable energy development

3.1. The motivation for sustainable development

Energy development is increasingly dominated by major global concerns of over-population, pollution, water depletion, deforestation, biodiversity loss, and global climate deterioration. For example, more than 20% of the Arctic ice cap has melted away between 1979 and 2003 [19], the "Living Planet Index", a metric which measures trends in the Earth's biological diversity, is estimated to have declined since 1970 by about 30%, and the "Ecological Footprint" (defined in [20] extended in [21]), which is the area of biologically productive land and water needed to provide ecological resources and services including land on which to build, and land to absorb carbon dioxide released by burning fossil fuels, rose 2.4-fold in the same period [22].[2] These trends are clearly unsustainable and alarming.

Obviously, energy consumption increases with population size, but not in a linear way: new population from developing countries typically requires more energy per capita than their parents did. While the rate of population increase had been dropping since the 2.2%/year peak in 1962 to 1.2%/year currently (Fig. 1), the increase from the current 6.7 billion people to the projected 9.6 billion in 2050 is 43%. The projections are obviously in some doubt, especially if the most populous countries, like China and India, do not continue[3] or start family size control. It would be impossible to achieve sustainable development if population size is not seriously addressed.

To prevent disastrous global consequences, it would increasingly be impossible to engage in large scale energy-related activities (or in any large scale activities for that matter) without insuring their sustainability, even for developing countries in which there is a perceived priority of energy development and use and power generation over their impact on the environment, society, and indeed on the energy sources themselves. While sustainability has various definitions [24–27], we can simply give here the original broad one that sustainable activities are such that they meet the current needs without destroying the ability of future generations

[2] Although there is an ongoing argument about the proper definition of the "Living Planet Index" and of the "Ecological Footprint" metrics, the general alarming trends appear to be correct.
[3] There are strong pressures in China to relax the one child per family policy.

to meet theirs, with a balance among economic, social and environmental needs.

3.2. Sustainability analysis

The use of the word "sustainability" is lately increasing in leaps and bounds although it is often not clearly understood by its users, and more often misused and abused. Vendors, institutions and even schools consider it very useful for their promotion, and vague enough not to be legally binding. The abuse has a wide range, including sustainable hamburgers (or the "Sustainable Hamburger Alliance"), sustainable Starbucks coffee (a cup costs 50-fold more than the value of the coffee), sustainable cosmetics, a fully-sustainable race car, sustainable university campuses, sustainable nuclear power, and so on. Probably the most general and earliest definition is *the way to meet the needs of the present without compromising the ability of future generations to meet their own needs* [24]. While providing an ethical and sensible direction, it is obvious that it is very difficult to quantify, since it does not define what the current needs are, what the composition of the future generations is, what their needs should be, which resources they would use, what the availability of these resources would be, and what the time frame is. The difficulty in defining, and indeed satisfying activities that meet the above sustainability definition, at least in the short term, brought rise to less demanding "practical" definitions, such as that formulated by industry/commerce: *a sustainable product or process is one that constrains resource consumption and waste generation to an acceptable level (my underline), makes a positive contribution to the satisfaction of human needs, and provides enduring economic value to the business enterprise* [28]. In fact, many utilities take a minimalist sustainability indicator, that of meeting environmental regulations, which they would have had to meet anyway just for compliance with the local laws.

Clearly, quantification of a project's sustainability metrics (indicators) is the first step in sustainable development, design and monitoring, but is admittedly very difficult because the systems are large and very complex, having technical, ecological, economic and societal components [25]. It is of vital importance to have where available, or develop where not, agreeable and unambiguous definitions of all the needed metrics. Unfortunately, even the more technical and economic metrics are not always well-defined and internationally agreed upon yet. For example, one would think that the "simplest" (i.e., most quantifiable and used) metrics of energy, exergy, Second Law, economic efficiencies, energy criteria considering environmental effects, and embodied energy and its payback are clearly and rigorously defined, yet we have discussed in some details in [29] their commonly used (or misused) variety of definitions and the resulting differences among some of them. Obviously, such differences could lead to very misleading conclusions.

All the needed metrics must obviously satisfy the laws and other facts of nature. Consideration of other facts of nature, such as reliable data on resources availability and accessibility, allows sustainable development planning that takes into account use of a resource both for single or multiple demands, and interrelations between the use of different types of resources. Cogent examples are the discussion of "peak oil", of availability of water for exploiting tar sands and oil shales, and for many other purposes, and of the possible competition over Lithium use between batteries for electric vehicles and fusion power generation (if either achieves massive use). Very important is the inverse relationship between the consumption of paid energy and of energy system other related resources, which often exists in processes. Two fundamental examples are (i) increasing energy efficiency by closer approach to the process thermodynamic reversibility requires a decrease of driving forces and the associated usually inevitable increase in equipment materials, and (ii) increasing use of renewable energy, that is typically available only with very low fluxes, thus requires large areas of energy collection A third example is the use of "waste" energy (such as "waste" or rejected heat), which is also of low exergy potential and thus requires large amounts of equipment, such as heat exchangers. An attempt to start the discussion on quantifying the depletion or resources and of the associated complexities is included in [30].

As an example of somewhat less used/known metrics is the concept of energy embodied in the production of a plant, in the materials produced by it, and in the materials and labor needed for its operation and for the distribution of its material products to the customer, and ultimate disposal and recycling aspects of a product. Moreover, careful consideration of embodied energy is of vital importance in renewable energy development, since renewable energy sources typically use, as discussed above, significantly larger amounts of material per unit useful energy output than conventional fossil and nuclear fuel plants.

Sustainability analysis contains significant uncertainties (cf. [31,32]), because the future is hard to predict ("The art of prophecy is very difficult, especially with respect to the future"), because the extent of the space of interest and its content/purpose may change with time, and because the life-cycle impact may vary with time due to legislation, discovery of new information, changes in attitudes, population, events, etc. Nevertheless, the process and methodology by themselves are very valuable in learning about the object of the analysis and about areas that need better information, and about ways that it affects the sustainability pillars of environment, economics and social impact. It is also useful for considering alternative approaches when all the inputs and scenaria are the same and reasonably correct.

Once all the relevant metrics for a sustainability analysis are determined, the objective function for the system optimization must be determined, they need to be aggregated with sensible weighting factors, and then an optimal solution must be found. This modeling and solution are also very difficult because the problems are dynamic, multi-scale and in many parts non-deterministic, and the data are difficult to collect, so better knowledge and tools are needed. Achieving sustainability requires a new generation of engineers and scientists who are trained to adopt a holistic view of processes as embedded in larger systems. Useful work to develop sustainability science is under way but much remains to be done.

4. Energy resources and conversion

4.1. The menace of price manipulation

A major concern (or opportunity?) is that the price of oil was lately growing very rapidly, from $28/barrel in 2003, to $38 in 2005, occasionally to above $80 in 2006, and peaking at $147 in 2008, but then precipitously dropping to $40 by the end of 2008 (and was about $70 in August 2009). The peak price is 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. It is also noteworthy that, so far, the international economy has proved surprisingly resilient to higher energy prices and continued to grow. It is also noteworthy that the Energy Intensity (energy consumption per $ GDP) continued dropping for both the OECD and other country groups [33]. The main concern at this time is therefore not so much the price level itself, but the huge, rapid, and seemingly unregulated price fluctuations, that seriously threaten the development of renewable energy, and of all energy systems for that matter. It is impossible to plan, establish, and maintain an energy business while the price of the conventional business competition can vary in this manner. Of course, if the high oil prices persist, it gives an opportunity for other energy sources, efficiency improvements and conservation to be introduced and thrive.

4.2. Global energy demand increase: the China example

Since China led the world energy consumption growth, it is noteworthy that it started from a very low per capita use base, where the per capita electricity consumption is 1/2 of world and 1/8 of people in the OECD countries [34]. Mostly coal is used, at electricity production efficiencies much lower than those of the world. The electricity generation shortage is somewhat larger than 35 GW, although it is being somewhat moderated by the global economic downturn. China is therefore engaged in an extremely ambitious and fast energy development program, which is unfortunately accompanied by major environmental consequences of coal, hydro, and fluid fuel development and transportation/transmission.

The remarkable growth in Chinese energy demand [14,35,36] is demonstrated by the fact that the average annual primary energy consumption growth jumped to 15.3% during the 3 year period of 2002–2004 and then further to 51.8% during the 3 year period of 2004–2007, from the 3.4% growth during the entire 11 year period 1990–2001. Similarly for the same periods, the annual electricity consumption jumped to 15.7% over 2002–2004, and then further to 61.5% during the 4 year period of 2004–2007, from 8.4% over the entire 11 year period 1990–2001.

Exponential growth is expected to continue since the economy development targets for the year 2020 include quadrupling the GDP with a 7.2% average annual growth rate, where the per capita GDP is planned to rise from $800 in 2000 to $3000 in 2020. In the same period the population is expected to rise from 1.27 billion to 1.5 billion, with urbanization expected to rise from 36% to 56% [34].

4.3. Fossil fuel energy

A remarkable global phenomenon is that despite the rise in consumption of fossil fuels, the quantities of proven reserves rise with time too, where the resources/production (R/P) ratio has remained nearly constant for decades, at R/P = 40 for oil, 60 for gas and about 120 for coal [1] (see Fig. 2 for oil). Although it is hard to know what the actual quality of the resources data is, an important reason, but perhaps not the only one, is that exploration and beneficiation of fuels increase with consumption and with price, and their technology is rapidly improving with increased use and need. While extrapolation of past R/P ratios is no guarantee that they will remain constant (or rise) in the future, it was becoming increasingly evident (cf. [37]) even before the more recent discoveries and the slowly improving technologies for approaching (but not yet attained) environmentally safe oil recovery from the vast tar sands and oil shales deposits, and from the relatively recently discoveries of shale gas and the start of its commercial recovery, that we would have sufficient fossil fuels for this century. This opinion is currently supported by most of the authoritative scientific and industrial sources. Even many of major “green” organizations now state that we will “run out of environment” before we run out of fossil fuel (cf. [22])

Oil, gas, and coal are transported massively both inside countries and internationally, via all means of land and water transportation. This has many negative ecological consequences that could be lessened with better technology. Electrical transmission systems are also expanding rapidly and to much longer distances, yet in most developed countries the core of these systems is antiquated and unreliable, leading not only to large transmission losses but also to severe insecurity of the distribution grid [38]. Unfortunately, highly insufficient funds were dedicated (by both governments and industry) to modernization and improvements of these distribution systems. For example, these areas were taken out of the 2009 USDOE budget, but the new U.S. administration has reversed this course and has given this topic relatively high (but still inadequate) priority.

Some forward-looking oil/gas companies have taken the CO_2 global warming problem as a business opportunity in making efforts to enable favourable fuel switches, increasing energy efficiency, supporting the development of renewable energy systems as well as hydrogen production and handling. Statoil ASA, for example, is particularly interested in developing a business from CO_2 capture and storage sine it has been injecting CO_2 at the Sleipner natural gas field since 1996 and has additional related projects which have shown that this storage was done safely and effectively [39]. While an excellent start and example, CO_2 sequestration by all different proposed methods is still a commercially unproven method requiring much additional R&D, testing, validation, risk analysis, and cost control [15].

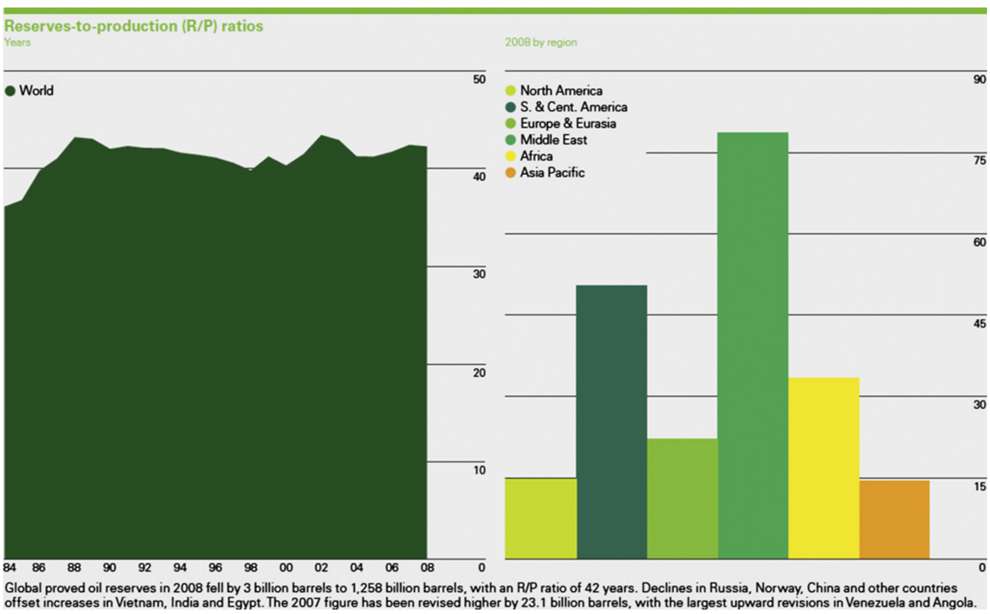

Fig. 2. The oil (Proved Reserves)-to-Production Ratio (R/P), 1983–2008 [1].

4.4. Nuclear power

While somewhat controversial both politically and factually, most of the available archival and authoritative sources agree that nuclear power produces, per unit power generated, only about half the CO_2 of wind power, 1/10 of solar PV and 30-fold less than natural gas (cf. [10,40–48]). Even the study by Lenzen [49] that predicts the highest CO_2-equivalent emissions of nuclear power generation as compared with all the other cited sources, at an average of 65 g CO2-e/kWh-el, that would make nuclear power emissions about twice as intensive than those of wind power, shows a wide range of 10 to 130 g CO2-e/kWh-el, where the lower end supports what most sources claim. The accuracy of the predictions depends strongly on the comprehensiveness of the life-cycle analysis and on the various conditions and assumptions for the sub processes in it. It is generally expected that the emissions will drop with improved technology of the entire cradle-to-cradle process. One simple example, out of many, is that new uranium enrichment technology in use requires only about 1/20 of the energy needed with the older diffusion systems. To alleviate at least to some extent the disagreements, a side-conclusion is that the responsible international bodies should strengthen he objective standardization of life-cycle analysis practices related to energy and emissions.

As of June 2008, there were 439 nuclear power plants in operation (5 less than in 2006) with a total net installed capacity of 372 GW(e), 5 nuclear power plants are in long-term shutdown, and 36 nuclear power plants are under construction [10]. The capacity factor of nuclear power plants as been increasing, reaching a remarkable average of 92% in the U.S.

While the use of nuclear power alleviates the global warming problem significantly (especially if electricity or hydrogen produced by nuclear means is also used for transportation), some of the leading problems associated with generating nuclear power haven't gone away. Hundreds of thousands of tons of spent nuclear fuel and other long-life nuclear waste are accumulating rapidly worldwide in temporary storage sites (many near the reactors that produce them), and hundreds of million tons of low-level waste from uranium milling are being left at mine sites and there is no solution yet for long-term radioactive waste storage or destruction. On top of that, the risk of proliferation of hazardous nuclear materials has become a much more serious problem (in some views the dominant one) in the past decade or so.

To respond to some of these problems, there are worldwide efforts to develop the "Generation IV" nuclear reactors [50–52] (with a target date of 2030) that would have the following main attributes: electricity price competitive with natural gas (3c/kWh), capital cost of $1000/kW, construction time of 3–4 years, demonstrated safety to regulatory agencies and to the public, and proliferation-resistance. These goals are positive but appear to be unachievable in that time frame without huge investments, if at all, which, if made, would diminish other energy development efforts.

Geological storage of high-level nuclear wastes is facing a strong public opposition, particularly because of the extremely long time, of the order of tens of thousands of years, or a million years according to a recent USEPA proposal [53], needed for its surveillance and monitoring. In fact, the new U.S. administration has decided this year to stop the development of the only planned long-term nuclear waste storage facility, Yucca Mountain, thus creating a serious setback to large scale nuclear power development till a new solution is found. A more reasonable method of dealing with this problem, if commercially feasible, is partitioning and transmutation of the long-life radioactive elements, currently considered to be done either in accelerator driven systems or in futuristic critical reactors.

Another serious problem is the scarcity of uranium for massive increase in nuclear power generation, if that power continues to be generated based on U-235, which is only 0.71% of the natural uranium. Based on a consumption of 180 tons enriched uranium per year by a 1 GWe nuclear power plant, and commercially available U-235 quantities, if 50% of the current world primary energy was produced using U-235, it would last for 14 yrs; If 50% of world electricity at the typical 33% nuclear power plant heat-to electricity conversion efficiency, the fuel would last for 29 yrs (the time estimates were made based on the data from [54–57]). This would be proportionally longer if the energy conversion efficiency was increased. Theoretically, the fuel would last for more than 1000 yrs if breeder reactors would be used. That could be solved by developing and commercializing breeding reactions that produce fuel without long-term wastes, such as those based on Th-232 that is a very abundant element in nature. Using Thorium as nuclear power reactor fuel, the released energy for a given quantity of the natural Thorium is more than one hundred times greater than that from the currently used U-235 driven nuclear reaction.

In the meantime, efforts are under way to extend the life of current plants to 60 years, from the originally planned 40 years.

Because of the increasing concern with global warming generated from the use of fossil fuels, and because no serious nuclear accidents have occurred during the past 20 years (since Chenobyl), public perception is improving, but is still not good and people have the feeling that they have to choose between greenhouse effect and acid rains associated with fossil fuels use, and severe consequences of possible nuclear accidents (even though their theoretical likelihood is very low, estimated at 10^{-6} per reactor-year), of nuclear wastes, and of use for warfare and terrorism. According to some opinions, "the choice is between the plague and cholera" [58].

4.5. Renewable energy

Renewable energy can supply the world's foreseen energy needs by orders of magnitude, but, with the exception of hydropower, geothermal, and wind, further development is necessary to make renewable energies cost competitive. The use of renewable energy is growing rapidly, but it provides now only about 3% of the world's primary energy consumption, with only about 1% from geothermal, wind and solar. It is used to produce 18% of the electricity, 86% of it by hydro.

Renewable energies successful implementation requires a realistic assessment. They have many clear advantages by not depleting the basic energy resource in the time frame relevant to current human interest, being typically less polluting and dangerous, their resources are much harder to control and manipulate than fossil and nuclear energy, and are emotionally more comfortable to many who are concerned about excessive industrial and large-corporate dominance. They also therefore have a strong socio-political emotional appeal that unfortunately sometimes tends to discount some of the important disadvantages of large scale use of renewable energy. This appeal, ironically, slows rational development of renewable energies and may have negative econo-social impacts. We must seek renewable energy solutions that are sustainable by definition, i.e. economically, environmentally, and socially. Some of the main challenges in massive sustainable implementation of renewable energies, are, briefly, their low energy flux that requires the use of very large areas and quantities of materials, consequent environmental impact, and transience (time-dependence with periods of no availability).[4]

[4] A fairly comprehensive but overly pessimistic description of the limitations of renewable energy can be found in [59].

4.5.1. Hydroelectric power

There is steady slow growth in hydroelectric power deployment and use, perhaps the most remarkable event being the recent (2008) addition of the 18.3 GW Three-Gorges dam in China (the world's largest electricity-generating plant of any kind), planned to be expanded to 22.5 GW by 2011. It is estimated that only 1/3 of the realistic potential has been exploited so far [60,61]. Growth will continue, also with micro-hydropower plants increasing in number, but it is also generally believed that the most economical and least disruptive large resources have already been exploited. At the same time, growth of other renewable energy sources is much less limited, and thus the current 86% hydropower share of all renewable sources use is expected to gradually drop. While the price of produced electricity in hydroelectric plants is relatively low, construction of such projects poses various environmental and social problems; this dam, for example, created an upstream lake of 600 km, displacing millions of people. It is also of importance to note that hydroelectric projects in warm climate vegetated regions cause significant release of CO_2 and methane. Many of these externalities are often not properly included in the electricity price.

4.5.2. Solar thermal

This includes heating, process heat, and solar-thermal power generation. Solar water heaters are widely used in all appropriate climates for about 50 years, and in most cases are economical without government incentives.

Solar-thermal power generation had a remarkable success in the hybrid solar-fuel plants using trough concentrators (originally installed by the Luz company), that have a capacity of about 0.5 GWe produced competitively in California, at a construction cost of $3000/kW [62,63]. An increasing number of similar power systems, are already operating and some new ones are proposed [64–66]. The basic concepts for such hybrid systems were studied by us both theoretically and experimentally (including the development of a novel turbine) much earlier under USDOE sponsorship, showing that the investment of about 25% high temperature energy, generated by combustion or solar concentrators, doubles the power generation efficiency, thus reducing the need for solar collectors by half when compare with systems operating at the lower temperature (70–100 °C for flat plate collectors in our system, and at a higher temperature in the Luz system), and reducing the capital cost [67–69].

Other promising solar-thermal systems are the central solar tower, and parabolic dish engine systems, several of which were built and successfully tested as R&D and demonstration units. These produce solar heat at high temperatures that could be comparable with those in fossil or nuclear fuel boiler-generated steam or gas.

The ambitious project, "DESERTEC" [70], originally proposed by the Club of Rome, heavily studied by the German Space Agency (DLR, cf. [71]) and from 2009 led by DII GmbH, an association of 12 companies (predominantly German), proposes to generate in 40 years electricity in the deserts of North Africa by concentrating solar power (CSP) plants and supply it via high-voltage direct current (HVDC) transmission lines as far as 3000 km to Europe, the Middle East, and North Africa (this distance, mentioned in the DLR reports, which could possibly be extended, reaches all of Europe except the Scandinavian and Baltic countries and is estimated to incur transmission losses of only 10–15%). For the planned output of year 2050 the system is predicted to occupy about 5600 km^2 (2500 km^2 for the solar field and 3100 km^2 for the electricity transmission), use no fossil fuels in its operation, use thermal storage, have a capacity of 125 GW to supply 15–20% of the entire region's electricity demand by 2020 and up to 80% (700 TWh) by 2050 according to the DLR reports [71], or 15–20% of Europe's electricity according to DII [70]. The cost of electricity by 2050 is predicted to be US$0.065 to US$0.165/kWh, and the entire system is estimated to require an investment of $555 billion.

4.5.3. Solar photovoltaic (PV) (partially from [72])

About 16.2 GWp photovoltaic power is installed nowadays, and it experiences exponential growth, 31% a year on the average over the past decade. The growth is primarily driven by government subsidies, which provide at least the benefit of developing industry and experience, as well as introducing the technology more widely to users. The EU goal is to attain 3000 MW there by 2010, and Japan's is 5000 MW. Multicrystalline silicone is still the dominant PV cell material, with an average efficiency of 15%. Thin-film flexible cell options are coming up, that would allow much easier installation even on surfaces that are curved. Large R&D programmes are under way in OECD countries, with Japan dominating, and recently a U.S. and European laboratory announced the first development of concentrating PV cells with an efficiency slightly above 40%.

In the U.S. the average installed total system cost (in 2007 dollars), prior to receipt of any direct financial incentives or tax, was $7.6/Wp; in Japan it was $5.9/Wp and in Germany $6.6/Wp [73]. The combined after-tax incentives were very high in these countries, in the US up to $5.7/Wp and even more elsewhere. For February 2010 the averaged global price of solar PV electricity (calculated for a sunny U.S. location, 5% interest, and 20 year system life) was 35.08, 25.3 and 19.50 c/kWh for residential, commercial, and industrial systems, respectively [74]. Conventional electricity prices in the U.S. were (for November 2009, the closest available date with data) 11.61, 10.25 and 6.87 c/kWh for residential, commercial, and industrial sectors, respectively [3], that is 2–3-fold lower. Since the price of solar PV systems in Germany, for example, is about 13% lower than in the US, and the price of conventional-fuel electricity is about double, the electricity price of solar PV there is roughly only up to about 30% higher than that of conventional-fuel electricity for the same sunny climate. It is noteworthy that both the price of conventional electricity and various government incentives are strongly influenced by political dictates rather than "free market" economics, and can thus relatively easily be changed. At the same time, it is nearly impossible to predict the effects of such government dictates on the actual long-term sustainable success of renewable energy deployment, especially when recalling that the conventional electricity generation competition is reducing costs too.

The cost of PV systems is high, making the produced electricity cost about two to five times higher than that of most other power generation sources, but is forecast to produce electricity at competitive price by the year 2020. A recent unexpected shortage of PV-grade silicon has increased its price by an order of magnitude, but this is already dropping back to the earlier prices as new manufacturing factories are coming on line.

4.5.4. Wind energy

Wind power progress is remarkably successful and expanding exponentially, with a capacity of 120 GWp (end of 2008) [75–78], forecasted to rise to an increase of 29 GW/year by the year 2014 [74,75]. For example, "Wind Force 12" [76] is a plan to globally reach by the year 2020:

- 12% of global electricity demand, equal to 3000 TWh
- Total installation of 1245 GW
- Installation rate of 159 GW/year
- An annual €80 billion business
- 2.3 million jobs
- Cumulative CO_2 savings of 10,771 million tonnes
- Cost reduction to 2.45€cents/kWh with installation costs of €512/kW

Wind power systems are increasingly economical [78], efficient, reliable, and big, with 5 MW turbines reaching a diameter of 125 m and height of 90 m. There is great interest in, and increasing deployment of, offshore units. Some of the objections, such as noise and wildlife impact, are considered to become relatively negligible with the development of new units, modifications in existing ones, and improved knowledge of plant siting. An important barrier limiting large deployment of wind power is the unavailability and inefficiency of the electricity grid, primarily to accommodate the fact that wind energy is intermittent and distributed and that grid energy storage is more economical than available alternatives. This barrier is common to all intermittent and unsteady energy sources, such as also solar and marine.

4.5.5. *Biomass energy*

While use of biomass has the very important benefits of contribution to the security of fuel, lower greenhouse gas emissions in some (but not all) cases, and support for agriculture, there are also some important concerns and obstacles. These include the fact that bioenergy production and policies have mostly not been based on a broad cost-and-benefit analysis at multiple scales and for the entire production chain, which is particularly true for bioenergy's impact on land and water use, on food production, and on agriculture. For example, while many publications extol the advantages of converting corn or other crops to ethanol, many of these analyses are flawed, at least in that they do not consider the entire system and cycle (an intense discussion is ongoing, cf. [79] as one example).

The major feedstocks used for biofuels production are currently directly or indirectly also used for food production, and over the past 5–10 years massive use of food crops such as corn, soya beans and sugar cane, to produce ethanol and bio-diesel fuels, was also accompanied by large increases in food price. In fact, many (cf. [80–83]), including the World Bank report that concluded "…large increases in biofuels production in the United States and Europe are the main reason behind the steep rise in global food prices" [83], blamed the food price increases on their diversion to fuel production. It is notable (cf. [84]) that the food price change trends followed those of oil: they rose exponentially from about the year 2000, peaked in August 2008 and then dropped by the end of 2008 to the 2006 levels, and in 2009 rose gain but only slightly. It is thus very likely that the food prices were affected more by speculation and energy prices than by feedstock shortages. Speculation is a major factor in price determination in a free market, and is triggered, often not closely related to the supply/demand situation, by large additional use of a commodity, such as food here, especially when the produced fuel price is government-subsidized and guaranteed. Some proponents of conversion of food to fuel claim that the diversion of food crops to fuel has not created food shortages and the observed price increases, but one could state that the markets have clearly reacted in this manner. With 1.02 billion undernourished people (Table 1), this is not a negligible concern.

Converting inedible plants to fuel, such as cellulosic source to ethanol, may be better but final sustainability proof is still absent. There is also a significant interest and effort in producing butanol which is a much better and more transportable fuel than ethanol, and in bio-diesel fuels.

IEA analyses and projections for biomass uptake by 2030 at competitive costs are 15 to 150 EJ/yr [9,84]. The proposed research needed for this major progress in using biomass [85,86] includes development of: (1) "new" biomass, via improved land use, waste utilization, and crop management, together with modified processing methods; (2) new methods of cultivating and harvesting aquatic organisms; (3) genomics and transgenic plants (e.g., to engineer plants and microorganisms that would yield novel polymers, or to maximize carbon for high-energy content), (4) new processes, such as enzymatic conversion of corn carbohydrates to polylactic acid (PLA) and other polymers, and combination of photosynthetic processes with special enzymes to create solid structures that would intercept sunlight and fix carbon into energy-rich materials, (5) improved use of traditional biomass (lignin and cellulosics) by more efficient gasification, enzymatic conversion of lignocellulosic biomass to ethanol, and (6) cultivation of hybrid rapidly growing plants (e.g., poplar or willow, switch grass).

It is extremely important to apply rigorous sustainability analysis and planning if massive use of biomass is sought.

4.5.6. *Geothermal energy*

Solar, wind, hydro and biomass energies are on the earth surface while extensive geothermal energy use requires digging to significant depth into the ground. Perhaps because it is "far from sight – far from mind", geothermal energy does not receive nearly the interest and investment that other renewable forms of energy do, despite some unique advantages. Besides being "renewable", geothermal energy is abundant, with a long-term potential that is more than 200,000-fold of current world energy demand [87–89], it is available at a steady supply rate and is thus much more usable than the intermittent and unsteady wind and solar, its land use is very low: smaller 3-fold than that for wind power generation and 10-fold smaller than solar or coal, and it can have very low or zero emissions of any kind with proper system design [88]. Nevertheless, issues of liquid and gas discharges, proper recharge (to maintain reservoir productivity, dispose of undesirable geothermal fluids and prevent land subsidence), water management, and risk reduction (induced seismicity, etc.) must be taken carefully into consideration in design and operation.

Its current and future use is for heating (including low temperature ground heat heat-pumps), combined heat and power generation (CHP), and power generation. GWe is produced worldwide from geothermal energy, and more than 100 years of experience have been accumulated. The electricity currently produced is typically competitive in price, at about 7–10 ¢/kWh, a price readily reducible by half [87,89].

Commercial geothermal wells are currently 60 m to 3000 m deep, with the drilling technology borrowing from the extensive experience of drilling for oil and gas (that reach depths of around 6000 m). Since the temperature of the geothermal heat source, whether hydrothermal, dry rock, or magma, increases with the depth, access to massive amounts of high temperature geothermal energy depends on drilling technology. Currently aiming at 10,000 m, the temperatures there are 400–600 °C at pressures around 1000 bar, thus having a very high power generation potential, but economical drilling to these depths and conditions is still under development.

5. Energy use

5.1. *Introductory comments*

In 2008, world primary energy use rose by 1.4%, with the increase *rate* steadily dropping since the recent 4.2% peak increase rate in 2004 (Fig. 3, [1]). The most recent drops in the increase rates can be explained by the rising fuel prices, the recent economic downturn, and increases in energy efficiency, but is likely to rise again soon with the economy, as the large developing countries in Asia keep improving their standard of living, China's rose by 7.2% (lowest since 2002, but accounted for more than half of global energy consumption growth), India's by 5.6%, and some significant drops are those of the EU – 0.56%, Japan – 1.9%, US – 2.8%, and

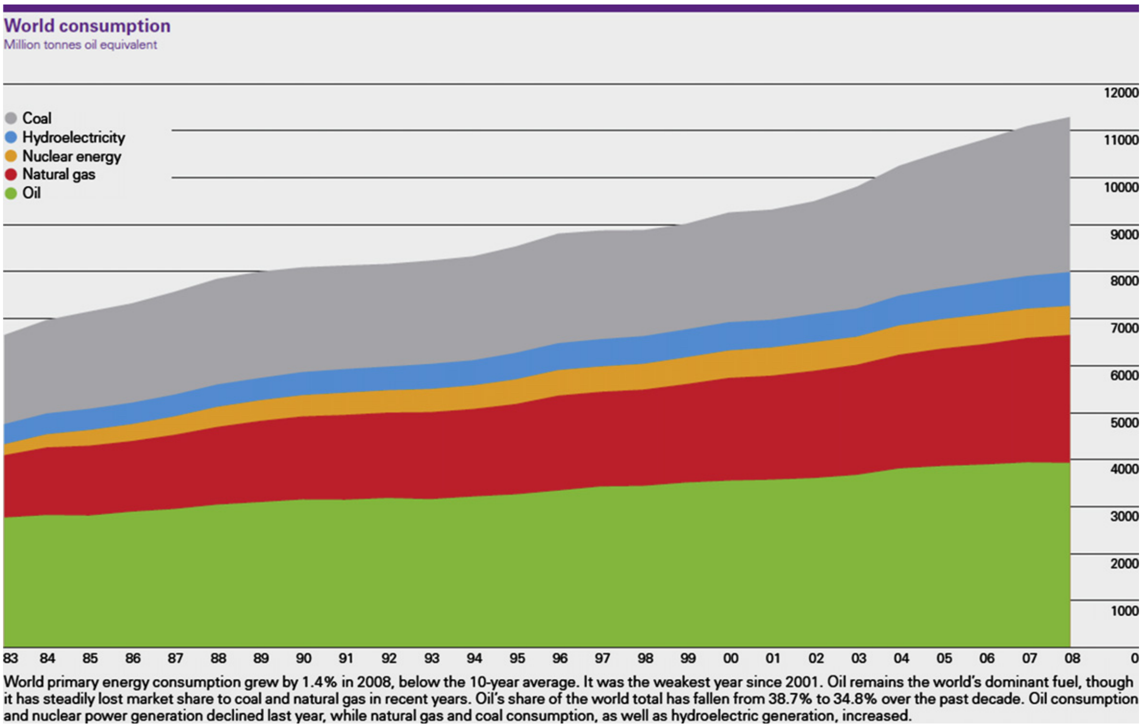

Fig. 3. World primary energy consumption 1983–2008 [1].

Australia – 4.2%. At the same time, there have been no physical shortages of the fossil fuels.

The total energy use split between industry, transportation and buildings/services/agriculture remains roughly the same, but the share of primary energy use for electricity generation is rising fastest, at a rate of about 3.2%/year, with coal being the current and growing major fuel [14]. The energy intensity (energy use per unit GDP PPP) is dropping globally by about 1%/year [33] despite the 2.9% annual rise in GDP.[5]

This section discusses conservation, the most imminent issue of exponential growth in electricity demand, and two of the energy demand sectors, transportation and buildings, as examples for inadequate and sometimes misguided attention.

5.2. Reducing demand: energy "conservation"

The energy use trends shown in Fig. 3 could, and should, of course be reduced by more judicious consumption. Rationally employed conservation is always the first step before other mitigation measures are taken, and is the easiest and cheapest to implement.

The omniferous politician, publisher, and scientist Benjamin Franklin (who also founded the University of Pennsylvania in 1740), a believer in conservation and frugality, has written "a penny saved is a penny earned". In the energy area in general, and in power generation in particular, one could safely say that "a Joule saved is worth significantly more than a Joule earned": it takes significantly more than 1 J of energy to generate 1 J of power. This is amplified several fold when one considers the resources and environmental impact associated with the construction and operation of a power plant or even a vehicular engine. It is clear therefore that the first priority in meeting the challenges of the coming century is energy conservation, but not implemented in a way that would deprive large fractions of humanity of basic comforts of life, nor in a way that has a very negative impact on productivity. A related example is the finding of a lifestyles of health and sustainability study conducted in the U.S. in 2008 by the Natural Marketing Institute (www.nmisolutions.comlclohas.html) that there are very few consumers (5–10%) who are willing to accept higher cost or lesser performance of a product that has environmental benefits. The majority felt that although environmental issues are important, they are not willing to make sacrifices [90].

Avoidance of consumption by measures such as higher energy conversion efficiency, reduction of blatant waste, and more modest lifestyles, offers the highest impact on the reduction of fuels and materials consumption, and importantly, on the associated undesirable emissions and environmental and political consequences (cf. [12]).

5.3. Future electricity generation

5.3.1. The fuels and technologies

From the 20.2 PWh of electricity generated in 2008, about 66% is produced from fossil fuel, 18% from hydropower, 14% from nuclear fuel, and the remaining 2% from geothermal, wind, solar, wood and wastes. Coal provides 62% of the fossil fuels electric power generation, gas 29% and oil 9%. Practically all of the coal- and oil-fired electricity generation is by Rankine-type steam power plants, and some of the gas-fired plants use combustion gas turbines. A small but increasing fraction of power generation is by combined cycle systems, using a topping gas turbine system and bottoming steam turbine one. Such plants have an efficiency approaching 60%, 35% higher than that of regular cycles, at a competitive capital cost. Nuclear power plants generate electricity via steam turbine Rankine-type cycles, with an efficiency of about 33%. It is noteworthy that this efficiency is much lower than those of fossil-fuel power plants because of the lower top temperature in the nuclear power plants, and proportionally increases the amount of waste heat discharge to the environment. Large hydropower plants

[5] Prior to the recent global economic turndown.

operate at efficiencies approaching 90%, and large wind power plants below 30%.

5.3.2. The future power generation problem and likely solution trends

The most eminent problem in future power generation 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 [3,14,91]. This translates to the stunning number of one 1000 MW power station brought on line every 3.5 days over the next 20 years, on average!

To mitigate associated negative effects of such massive increase, it would increasingly have to be done sustainably.

Because of its abundance in the most energy consuming countries such as China, the USA, parts of Europe, India, and Australia, coal is likely to be increasingly the main basic fuel for these plants, partially after conversion to gaseous or even liquid fuels. Compared with other energy sources, coal-fuelled power plants also produce the cheapest electricity. The extensive use of coal will increase the need for more stringent mining and emissions controls and attention to other ecological and social problems associated with a coal economy. The reduced emissions IGCC (Integrated gasification combined cycle) plants, increasingly with CO_2 capture (CC), are thus likely to be receiving major attention: there are about 160 commercial projects in operation/ constructions/design, 450 gasifier vessels, production of 68,000 MW thermal energy and of 430 million normal cubic meter per day of syngas [92,93]. Intensive efforts are made for the adoption and development of this technology in the Asia-Pacific region (cf. [94,95]), but the worldwide progress to commercialization is still slow, mostly hindered by cost and insufficient lack of incentive.

As discussed in Section 4.4 above, nuclear power plants will continue to be constructed at least for special needs, such as those of countries that have much better access to uranium than to fossil fuels. Furthermore, if carbon emissions are made expensive enough, nuclear power plants would become more viable.

As discussed in Section 4.1 above, the economic competiveness of all renewable energy power generation plants depends of course on the cost of the fuel used by fossil or nuclear power plants. Wildly fluctuating and unpredictable oil and gas prices make reliable planning of renewable, or even nuclear, power generation nearly impossible.

Wind power generation is typically competitive when oil prices are around \$60/barrel, currently supplies $\sim$2.5% of the world electric generation capacity of about 4 TWe and 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 is estimated to be marginally competitive at an oil price above \$150/barrel, and will continue increasing in efficiency and decreasing in price but may not reach parity in the coming decade. Hybrid solar-thermal power plants which use solar heat at a lower temperature and the fossil fuel for raising the temperature of the working fluid prior to its inlet to a turbine, of the type described in [62–64,67–69], are becoming competitive. The time-dependency of wind and solar power introduce major problems that could be resolved by use of energy storage (expensive and often unavailable when hydro or compressed air storage are considered), or grid storage.

Hydroelectric power provides most of the $\sim$6% contribution of renewable energy to the total energy supply and shows steady but slow growth.

Biomass use for power generation will continue to increase, slowly, mostly by combustion of agricultural municipal waste, wood, and of landfill-generated methane.

Improvements and technological advances in the distribution and storage of electric power must and will continue. These are needed for accommodating varying demand with electricity generated by non-renewable conventional fuels, and even more importantly so when using renewable intermittent sources such as solar and wind. Also, development of superconductors to become commercial and affordable must continue, as they have great potential in increasing electric systems efficiency and allowing economical longer distance transmission, say from energy-rich to energy-needy regions.

5.3.3. Thermal power generation progress

Driven by fuel cost and by competition, remarkable progress is being made by private industry (with some assistance from governments) in efficiency improvement, and in emissions and cost reduction of both internal and external combustion power generation equipment [96]. Commercial Diesel engine efficiency reached about 43% and is likely to reach 55% in a few years, compliant with strict emissions regulations. Advanced internal combustion engines, such as the homogeneous charge compression ignition (HCCI) have peak efficiencies of about 32% with expectations to reach 45% in a few years. Using fossil fuels and other high temperature heat sources, the combined cycle power generation plants are the most desirable, approaching efficiencies of about 60% even at present, having less emission than other plants when using natural gas, and having reasonable cost that would keep decreasing as the technology advances further. To use solid fuels, the ongoing development of IGCC plants, with or without carbon capture, is of great importance. IGCC plants have reached a respectable efficiency of 42% at an investment cost of \$1700–\$2100/kW, and may with further development reach 60% in a decade or so. Carbon capture and storage is estimated to reduce the efficiency by about 25%, and increase the electricity price by about 25% [97].

It is noteworthy that the improvements in efficiency of all above described systems are obtained in compliance with increasingly strict emissions regulations.

5.3.4. Fuel cells and hydrogen

Very active development of fuel cells, encouraged by the governments of practically all industrialized nations, is ongoing, primarily aimed at using hydrogen fuel in transportation, but also for large stationary power generation units. It seems that this major effort has presently peaked, because various important technical issues must be resolved before fuel cells attain significant market penetration, and the cost must be reduced by an order of magnitude. Conducting vigorous R&D is reasonable, but has to be balanced against equally important support needed for improved internal and external combustion engines that have in some cases already attained efficiency higher than those of fuel cells, at much lower costs.

Hydrogen derived from coal and biomass was the primary R&D goal, to produce it at prices competitive with crude oil equivalent when integrated with advanced coal or solid biomass power systems (cf. [98]). Despite its advantages in producing near-zero harmful emissions *in the process of its conversion to power*, and the activities so far, the general opinion of the scientific community in this field is that widespread use of hydrogen as fuel in the foreseeable future appears to be doubtful, because of the high-energy demand and emissions in its production, and issues of safety, storage, and distribution. It appears that the new U.S. administration has reduced this effort significantly now.

5.3.5. Micropower systems

There is an increasing interest in the construction and use of very small, of the order of 1000 μm, power generation systems for various applications, ranging from the military to the medical (cf. [99–102]). Such systems include miniaturized thermal power cycles, and direct energy conversion systems including fuel cells [103], mostly intended to replace batteries as much longer operation and low weight/volume devices. Since the power produced by such a device is of the order of milliWatts at best, it does not at first glance appear that they will be used to produce a significant fraction of the overall power demand. At the same time one cannot help but note that use in very large numbers can create significant worldwide capacity. For example, the many very low capacity computers which are increasingly being used in just about any electrical device, including cars and home appliances, constitute by now a computing capacity far exceeding the total capacity of the existing personal, workstation and mainframe computers, and the total power produced by batteries of various types is of the order of magnitude of the total electric power generation.

Micropower generators pose very interesting research, development, and construction challenges, many related to the very complex flow, transport, and thermodynamic phenomena. The extraordinary benefits of micropower generators in many known and yet unknown applications make the challenges associated with their development very worthwhile.

5.3.6. Further-future paths: fusion and power from space

The major appeals of nuclear fusion for power generation are: (a) that its fuel is composed of rather abundant elements, deuterium that is plentifully available in ordinary water (a liter of water would thus have an energy content of 300 l of gasoline) and tritium that can be produced by combining the fusion neutron with the abundant lithium, and (b) the radiation from the process is very low and short-lived (but the environmental problems are not negligible). Fusion reactions have enormous energy density (337 TJ/kg for D-T, second is enriched uranium nuclear fission in light water nuclear reactors at 3.46 TJ/kg, and for comparison, crude oil at 46 MJ/kg), which is both a big advantage and disadvantage. Fusion has the potential to be a very abundant and relatively clean source of energy, with minimal global warming emissions. The biggest problem, not solved after more than 50 years of research, is to create a fusion reactor that continuously produces more energy than it consumes. Past predictions of success and commercialization had a 25-year target (repeatedly…), and those have increased to about 35 years based on the ambitious multi-national ITER program that is constructing a 500 MW magnetic-confinement fusion test facility in Cadarache, France [104].

Another approach considered since the 1970s is generation of electricity in space (cf. [105–109]) for terrestrial use, from a number of energy sources, including solar, nuclear, and chemical. The generated power can be transmitted back to earth by a number of ways, including transmission by microwaves or laser beams, or on-site manufacturing of easily transportable fuels for electrochemical or combustive energy conversion.

This is a very complex method, but in view of the rising demand for energy, the diminishing fuel and available terrestrial area for power plant siting, and the alarmingly increasing environmental effects of power generation, the use of space for power generation seems to be rather promising and perhaps inevitable in the long term: (1) it allows highest energy conversion efficiency, provides the best heat sink, allows maximal source use if solar energy is the source, and relieves the earth from the penalties of power generation, and (2) it is technologically feasible, and both the costs of launching payloads into space and those of energy transmission are declining because of other uses for space transportation, dominantly communications.

The technology for such systems is in principle available, and the major obstacle is the exorbitantly high cost, which under current conditions requires the reduction of all costs by orders of magnitude; for example, space transportation costs by at least a hundredfold: to less than $200/kg into orbit, for competitiveness.

Perhaps most interesting is the change of paradigm that space power presents: Earth becomes less of an isolated closed system. National and international work on this subject should be invigorated so that humankind will continue having the energy it needs for its happiness and, indeed, survival.

5.4. Energy and transportation

5.4.1. General comments and obvious remediation deficiencies

Transportation accounts for 28% of global energy use and 23% of global carbon dioxide emissions [14], and the number of vehicles and distances traveled is forecast to continue increasing rapidly, at 3.1%/year, especially in the developing countries [33]. The amount of energy use is obviously affected directly by the fuel efficiency of the vehicle but also importantly by traffic conditions such as number of stops (starting, acceleration, and idling), which in air travel is demonstrated by idling while on the ground, holding patterns over airports, and detours. Furthermore, while the total amount of energy used is of dominant importance nationally and globally, its values normalized by vehicle occupancy and/or cargo weight are invaluable for both national and individual transportation planning. Finally, the time needed to travel between origin and destination, severely increased by poor traffic design and control, with the associated congestion, not only waste precious time of travelers, but also raises threats to life and health. These outcomes of poor traffic design and management have serious negative economic, environmental and social impacts both individually and nationally.

As obvious as all this is, a serious problem is that governments, and even individual vehicle owners, seem to pay much more attention to improving fuel efficiency of vehicles in miles per gallon (mpg) or km/l, (say the U.S. Corporate Average Fuel Economy (CAFE) compulsory standard)[6] than to any of the other parameters, which in fact may have more impact than vehicle mpg (km/l) alone. It is also recognized that increasing fuel efficiency has a significant "rebound" effect, where vehicle owners drive longer distances and purchase higher horsepower vehicles because the fuel cost per mile drops. The U.S. data [110–112] show that the distance traveled (per vehicle, and overall, by the vehicles to which the CAFE standard applied) indeed increased by nearly 25% but the overall fuel consumption dropped by about 25% too, after the standard's establishment. An obvious negative outcome of an increase of distance traveled is commensurately higher congestion and travel time for the same distance, with other related negative consequences. Even purely socially, it is inappropriate that vehicle users impose congestion and other problems on other road users without incurring any costs, which if imposed, would at least signal materially a more proper social behavior. The World Bank estimates that air pollution and traffic congestion lead to enormous losses in health, time, and ultimately economic growth [113].

Notably, the rebound effect had also a role in the fact that in the U.S. the average horsepower per vehicle increased 2.2-fold in the same period, mostly as a result of the customer trend to sport-utility and other large vehicles. This counter-intuitive fact was in large part due to increases in the efficiencies of the engine and transmission, use of more aerodynamic and light materials, and

[6] The sales weighted average fuel economy, expressed in miles per gallon (mpg), of a manufacturer's fleet of passenger cars or light trucks with a gross vehicle weight rating (GVWR) less than 8500 lbs, manufactured for sale in the United States, for any given model year.

friction losses reductions. Since the horsepower increase is a customer preference but not necessity, one can conclude that at least a 2.2-fold reduction in fuel consumption could be achieved if car horsepower was reduced to the 1980 levels, especially in view of the fact that even that horsepower was excessive and much higher than that of average cars in say Europe and Japan.

Rebound can be controlled by several means, especially by stricter management of demand, including the use of pollution, congestion, and road charges that would also correct the relative prices of private and public transport. Lastly, it is obvious that rebound, as well as overall fuel use for transportation can be reduced by government-imposed taxes on fuel, raising them to that finely defined level that discourages frivolous use but still allows effective economic progress and reasonable human happiness. In fact, most of Europe, where gasoline and diesel oil price is roughly 3-fold higher than that in the US, has been taxing these fuels heavily for many years, with the tax being about 10-fold higher than in the US. While indeed curbing fuel consumption to some extent, plain taxation is a very political matter that is also fraught with negative impacts. To mention some, it transfers more of the individuals' and companies' money to government control, thus both reducing their purchasing power and allowing government inefficiencies to manage that money, it may reduce motivation for productivity, raises the cost of goods and reduces competitiveness, and increases social inequity among the rich and the poor. Indeed, such taxation must be considered by using sustainability science methodology that considers all impacts, and an optimum should be sought.

5.4.2. Rigorous sustainability analysis of transportation development: absent but sorely needed

In view of the important economic, environmental and social impacts of transportation, where it is also generally regarded that the negative impacts on society far outweigh the benefits to individuals when private transportation is considered, it is surprising that formal/rigorous sustainability analysis is hardly used in transportation planning and development (cf. [114]). To begin with, sorely needed are some commonly-accepted integrated metrics, that combine vehicle fuel consumption (mpg or km/l), passenger occupancy or cargo weight, travel time between points, emissions, other parameters affected by traffic control and its effectiveness, such as higher accident likelihood in congested traffic, parking, etc, as well as the effects of the physical presence of the road system and its infrastructure. Recognizing the same need, Maddison et al. [115] discuss extensively the "true cost of transport" and offer suggestions for quantitative indices for effects on transportation-generated species and noise pollution on human health and on the related economic consequences, cost of travel time due to congestion, road damage, accidents and their economic valuation. They also describe a possible economic aggregation of these negative impacts and conclude that "Having a sustainable road transport system means making each road user pay at least the full marginal cost of his or her journey. At this moment users of the road network pay only a fraction of these costs…". Such payment/taxation is highly complicated by the fact that it would require extensive monitoring (both human and instrumental) and always leaves the question as to what the fees/taxes are used for and to what effect. Wisely designed investment into effective public transportation is probably one good target for such revenues, careful investment in improved roads and traffic management with rebound protection, as well as in development of sustainable neighbourhoods that require less transportation, and remediation of transportation-contaminated sites, are yet some others, A year later, the US National Research Council published a report [116] that looks into sustainable transportation, primarily focusing on emissions. It identifies different transportation effects and discusses some possible solutions, most of which are recommendation for further R&D and expansion of education and public awareness, but offers no quantitative sustainability indices, nor practical policy recommendations.

The World Bank has a description of transportation sustainability that addresses all three pillars [113]:

> *Economic*: "requires that resources be used efficiently and that assets be maintained properly… To be economically and financially sustainable, transport must be cost-effective and continuously responsive to changing demands".
> *Environmental*: "requires that the external effects of transport be taken into account fully when public or private decisions are made that determine future development… Transport has significant effects on the environment that should be addressed explicitly in the design of programs "
> *Social*: "requires that the benefits of improved transport reach all sections of the community" focused on "providing the poor with better physical access to employment, education, and health services."

The World Bank report contains many important issues that must be considered in the development of sustainable transportation and recommends some ways to implement them, but like the original Brundtland report [24] on sustainability in general, and like all published material we found about sustainable transportation, it just presents an ideological wish list without providing any quantitative metrics nor recommends their development. More recently, the World Bank did start employing sustainability indices when considering loan applications.

The simpler aspects of sustainability quantification, such as methods for evaluating fuel consumption and travel time, are well understood (cf. [117]). The International Energy Agency (IEA) has developed the ASIF equation [114,118] to calculate the emissions of transportation to the environment, but it does not at all address the economic and social aspects. The large interest in it is generated by the emissions issue, intensified more recently by global warming, and seems to inadvertently overshadow the other sustainability aspects of transportation; it must be recognized that even the environmental issue is not limited to emissions. Furthermore, the variables in it are not independent of each other and thus make its use for sensitivity analysis very difficult.

One of the noteworthy specific deficiencies of all transportation sustainability recommendations and metrics is that none considers travel time in a fully quantitative way. Since travel time increases due to congestion, a commonplace experience, this demonstrates not only disrespect for individual passengers' time and money, but also blatantly disregards the negative impact on the national economy. At the same time it has been recognized that shortening travel time between origin and destination also has its rebound effect in increasing traffic volume, with the associated increase in overall energy use and emissions. Good traffic and demand management can be used to control such outcomes.

Another leading deficiency is that the interactions between economic, environmental and social requirements are not considered, and they are treated as if they were independent variables. Methods essential to sustainability analysis, such as definition of an objective function and of weighting factors for the different influencing parameters, agglomeration of indices, and subsequent optimization, are not used at all. A frequent "excuse" is that even qualitative improvements are very difficult to implement on a significant scale, because of the enormous magnitude of the required financial investment even just to maintain the transportation infrastructure, let alone new development, and the existence of various seemingly insurmountable political barriers. It is a cogent argument by itself, but using it to avoid the application of quantitative sustainability analysis and optimization just helps in perpetuating the problem rather than progressing toward its solution.

5.4.3. Trends in private vehicle development

Concern with the impact of automotive emissions on air quality and on dependence on oil has at first focused on the use of hydrogen and fuel cells. Recognizing by now the difficulties with commercializing this approach, focus has shifted to plug-in hybrids (PHVs) and electric vehicles (EVs). They could diversify transportation fuel sources beyond petroleum and could decrease GHG emissions if low-carbon electricity is used. Since they generally require five to twenty times larger batteries, breakthroughs in battery cost, weight, volume, performance and safety will be needed to achieve widespread commercial use. While the IEA Outlook [14] does not anticipate significant PHV and EV penetration by 2030, ongoing developments indicate that this may take place much sooner.

5.5. Energy and buildings

Buildings (residential + commercial) consume about 30–40% of the world's primary energy [14,119], or 16% according to [33][7]; it is about 40% in the US and EU and 50% in the UK. Buildings account for about 45% of the anthropogenic CO_2 emissions, and are thus an important target for reducing both energy use and emissions. Some comments are made here about only two important sustainable building development issues: the perennial difficulties of implementing massive improvements in this sector, and separately on the promising yet challenging development of "Eco-efficient" or "Living" buildings.

It is of fundamental importance to start from the understanding that; (1) unlike some of the other energy uses, the need for buildings of some type is absolute, not an optional energy use, (2) their purpose is to provide comfortable, safe, healthy, and pleasant shelter, (3) while their energy consumption (that also generates the associated emissions) is often the major (and increasing) fraction of a building's life-cycle annual cost, it typically still constitutes a very small fraction of their residents'/owners' income [120] and thus the users/owners, and for that matter governments whose interest span is typically limited by their tenure (that is much shorter than a building's life), don't have a strong incentive to make energy-related improvements, and (4) while improvements needed for reducing their energy consumption and emissions are in many cases technologically available with an acceptable cost-benefit ratio when based on life-cycle analysis, residents and owners usually do not have a financial interest in the long-term (building life).

Construction and operation technologies, such as better thermal insulation, reduction of fresh air intake, passive design, intelligent, demand-governed control and operation, ambient exposure control, natural lighting, better HVAC equipment and appliances, as well as integration of renewable energy, are well known, and are widely used to some degree or another. It is also well known that design and siting of new settlements can reduce energy and environmental impact by densification, reduction of need for automobiles, and appropriate planted landscaping. There is also an ages-long outcry for better cooperation between building architects, engineers, operators, users, owners, energy supply utilities, and lenders, but it often does not work well enough, mostly for the above-mentioned financial reasons.

It is also well known and widely practiced that improvements can be implemented by legislation, such as mandated by many governments and institutions. It is noteworthy that while institutions may often not realize tangible benefits from such improvements, the intangible benefits may be important; for example the public image of environmental concern may help sales by companies and student recruitment by universities. It would of course be much more effective if the tangible benefits would become significant, using market forces rather than just legislation. Financing practices that monetize long-term energy costs in near-term investment decisions can make a major contribution to this effort. A number of such initiatives have been implemented in several countries, including the European Union and the United States. [121,122] (just recently the European Parliament came to an agreement (not ratified yet) to require "nearly zero" energy building standards (by improving building efficiency and using renewable energy) by the end of 2020 [123,124]). Obvious actions in that direction would be to charge the real cost of environmental effects, from cradle to cradle, and to reduce the cost of technological improvements and building operation. While the former measure requires legislation, it corrects the blatant and harmful absence of penalties for behavior (to include embodied energy and environmental impacts of the used materials and processes) that is clearly harmful and quantifiable. Why, for example, is it socially acceptable legislation to impose a fine of $500 for discarding a chewing gum wrapper along a highway, yet the emission of tons of environmental and global warming pollutants carries no penalty?

Another argument for preferring "free market" approaches (that assign the real life-cycle cost of buildings and their operation, including all externalities, and properly regulated, of course!) over government intervention is the inevitable bureaucracy, complexity, cost and occasional corruption potential (among both regulators and users, "green-washing" has become a common expression) that governmental intervention typically introduces. An anecdotal example is the report that it has cost $50,000 to LEED[8] certify a rather small (930 m^2) building, while LEED advertises a cost of only $1750. The additional costs are in the paperwork, commissioning fees, computer modeling, fees, etc.

On the other topic in this Section, "Eco-efficient" or "Living" buildings (depending on the namer or user, these names describe somewhat different features, but the intent here is the same), which not only reduce their negative environmental impact but also help heal and improve the environment. Buildings and the built environment in general, including roads, can reduce the global warming effect and environmental pollution not just by reducing energy consumption and by the choice of materials that are less harmful in those ways to the environment (attributes that characterize what is typically known as "Green buildings"), but also by direct interactions with the environment. Some examples of such interactions include surface treatment and orientations that reduce their absorption of solar energy and increase its reflection (that help mitigate "heat islands"), use of plants (green roofs for example) to absorb CO_2 and even grow usable produce, surface treatments to absorb some pollutants, recycling water, and collecting rainwater. In calling them "living buildings" they are compared to a flower as it operates in relation to its environment by being actively responsive, drawing its resources from the ground and sky it inhabits, maximizing efficiency and comfort, and

[7] Exxon did not answer a question about this discrepancy.

[8] LEED is a commonly used green building certification system, to verify that a building or community was designed and built to improve energy savings, water efficiency, CO_2 emissions reduction, improved indoor environmental quality, and stewardship of resources and sensitivity to their impacts. It was developed and is maintained by the US Green Building Council, a non-government organization.

improving its surroundings both by environmental restoration and by providing beauty [125]. Considering the worldwide rapid rate of urbanization and road construction, these are promising but challenging approaches that require further research, development, and testing to reduce cost and ensure robustness.

6. Some recent energy R&D budgets and trends

6.1. The United States

2009 is an important year for energy in the U.S. because the voters turned the 8-year leadership by a Republican party government and president into the Democrat party hands, alongside with the historically significant election of President Barack Obama. The new administration, following basically its campaign promises but also faced with the immediate worst economic downturn since the great depression, started making significant changes in many directions, including in the energy and environment areas. In this section I briefly summarize the U.S. Department of Energy (DOE) fiscal year 2010 budget request that pertains to the energy and environment area [126,127] and discuss changes relative to past years under the previous administration. 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 economic uncertainty, U.S. dependence on oil, and the threat of a changing climate (reducing U.S. carbon emissions) by transforming the way the US produces and consumes energy. Most impressively in purpose and magnitude, an additional one-time allocation of $38.7 billion from the American Recovery and Reinvestment Act of 2009, is to be added to the 2010 year DOE budget and used (typically starting in 2009 with a duration of about 3 years) to accelerate investments in energy conservation and renewable energy sources ($16.8 billion), environmental management ($6 billion), loan guarantees for renewable energy and electric power transmission projects ($6 billion), grid modernization ($4.5 billion), carbon capture and sequestration ($3.4 billion), basic science research ($1.6 billion), and the establishment of the Advanced Research Projects Agency (ARPA, $0.4 billion), all "to help jumpstart the economy and save and create jobs at the same time". To characterize the enormity of this expenditure, the $38.7 billion from the American Recovery and Reinvestment Act is more than 6-fold higher than the DOE annual energy R&D and Science budget and about 16-fold higher than the annual amount that the EU 7th platform allocated for R&D in roughly the same areas.

The budget emphasizes (a) clean, renewable energy generation, (b) energy efficiency and conservation, (c) electric grid modernization, (d) other low emission energy technologies focused on low-emissions transportation, safe and reliable nuclear energy, and cleaner coal, and (e) improved energy information data and analysis.

Proposing to use a cap-and-trade process, the current US administration plans to reduce the U.S. greenhouse gas emissions by 14% under the 2005 baseline by 2020, and by 83% below the 2005 baseline by 2050 (similar to the IPCC proposal).

It includes $1.2 billion for three new approaches to augmenting research and development efforts:

Energy innovation hubs

Establish eight multi-disciplinary Energy Innovation Hubs at a total of $280 million to address basic science, technology, and economic and policy issues hindering the Nation's ability to become energy secure and economically strong while reducing Greenhouse Gas (GHG) emissions. This initial set of research Hubs will explore solar electricity; fuels from sunlight; batteries and energy storage; carbon capture and storage; grid materials, devices, and systems; energy-efficient building systems design; extreme materials; and modeling and simulation (the latter two for nuclear energy).

Energy frontier research centers

The existing 16 Energy Frontier Research Centers (EFRCs) will continue to be supported.

These centers, involving almost 1800 researchers and students from universities, national labs, industry, and non-profit organizations address the "full range" of energy research challenges in renewable and low-carbon energy, energy efficiency, energy storage, and cross-cutting science.

Advanced research projects agency-energy (ARPA-E)

ARPA-E with $410 million funding, is a new DOE organization to advance high-risk, high-reward energy research projects that can yield revolutionary changes in how we produce, distribute, and use energy

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.

Outside of the huge injection of the funds from the American Recovery and Reinvestment Act of 2009, the USDOE budget dedicated specifically to energy R&D was requested to be reduced in the 2010 budget by about 11% from the 2009 (past administration's) amount, to about $4.2 billion. It additionally includes perhaps about $2 billion in basic energy sciences (out of the $4.9 billion USDOE Office of Science budget after its 3.9% increase, that funds also several other areas which are not directly related to energy). Thus the approximate total requested R&D and basic sciences budget for energy is about $6.2 billion.

Out of the USDOE energy R&D part, the programs of energy efficiency and renewable energy continues to increase its dominance to 58% (from 53% in 2009 and 48% in 2008) relative to those of fossil energy and civilian nuclear energy,[9] basically at the expense of the latter that dropped to 19% (from shares of 20% in 2009 and 27% in 2008).

In more detail, the most important budget changes include:

- 3.9% increase ($263 million, after the 19% increase in 2009) in the DOE's *Science* programs (nuclear physics including major facilities, materials, nanoscience, hydrogen, advanced computing).
- 6.9% increase (vs. the 27% decrease in 2009) in the *Energy Conservation and Renewable Energy* program, with major gains in solar (+89%, following a +37% increase in 2009), wind (+36%), geothermal (+14%), vehicle technologies (+22%) to increase efficiency (focus on the plug-in hybrid electric vehicle, PHEV, to support the Presidential goal of deploying 1 million PHEVs by 2015 that can get up to 150 miles per gallon, 64 km/l) and enable operation on non-petroleum fuels, and buildings technologies (+70%); drop of 60% (after the 31% drop in 2009) in hydrogen and fuel cells and drop of 25% in water power. DOE's efforts on biofuels would focus exclusively on developing non-food/feed based cellulosic feedstocks, and ethanol production technologies.

[9] Excluding consideration of the GNEP program, described below.

- ➢ 21% decrease (compared with the 23% increase in 2009) in the *Fossil Energy* program to $882 million, includes $404 million for clean coal technology, and $25 million for gas hydrates ("ultra-deepwater natural gas"). Very noteworthy is that here the Recovery Act is to provide *$3.4 billion* additionally for carbon capture and storage (CCS) and for the Clean Coal Power Initiative (CCPI), and more than offsets the $229 million decrease in the DOE's annual Fossil Energy budget.
- ➢ No capacity expansion for the 727 million barrels Strategic Petroleum Reserve (planned earlier to be expanded to 1 billion barrels beginning in FY 2008 and later to 1.5 billion barrels). The rapid increase in oil prices was one of the important reasons for that decision.
- ➢ Investment tax credits (typ. 30%) of $3.15 billion was allocated in 2005 and 2008 for accelerating commercial deployment of technologies central to carbon capture and storage, plus an additional $2.3 billion allocated this year from the American Recovery and Reinvestment Act of 2009 for manufacturing facilities that produce specified advanced energy products such as renewable energy power systems, automotive storage systems, energy conservation, carbon dioxide capture and storage (CCS) technologies and other systems designed to reduce greenhouse gas emissions.
- ➢ A 4% reduction in the fission nuclear energy program, to $761 million, aggravated by the fact that its R&D portion is reduced by 22%. The program continues to be aimed at developing advanced nuclear power for meeting energy and climate goals, at developing advanced, proliferation-resistant nuclear fuel cycle technologies and at maintaining the national nuclear technology infrastructure. The highlights are:
  - ○ Work will continue on nuclear waste storage and disposal options, and "Generation IV (Gen IV)" advanced nuclear reactors, including the sodium-cooled fast reactor, molten salt reactor, supercritical-water-cooled reactor, lead-cooled fast reactor, very high temperature reactor, and the gas-cooled fast reactor (this is also the recommendation of the Generation IV International Forum [52])
  - ○ Seemingly termination of the $302 million Global Nuclear Energy Partnership (GNEP), launched in 2006 "to promote nuclear power in the United States and around the world and promote nuclear non-proliferation while developing new types of spent fuel reprocessing plants and fast-neutron reactors", with a main focus to speed the deployment of a commercial-scale nuclear fuel reprocessing plant in the United States.
  - ○ All funding for development of the Yucca Mountain facility for a permanent geologic storage site for spent nuclear fuel and high-level radioactive waste has been eliminated. The Administration intends to evaluate alternative approaches for meeting the federal responsibility to manage and ultimately dispose of spent nuclear fuel and high-level radioactive waste from both commercial and defense activities. This is a remarkable reversal of past year's decision to invest an additional $495 million for that facility (after spending about $13.5 billion (2007 value) over the past 26 years), touted all along as the main U.S. solution to its nuclear waste disposal.
- ➢ $4.6% increase (to $421 million) in the fusion program, including continuation of the contribution to the multinational ITER program;
- ➢ A 52% increase (to $208 million) in the electricity delivery and energy reliability program. A long overdue attention to this historically underfunded but critically necessary program, that addresses clean energy transmission and reliability, smart grid R&D, energy storage, cyber security of the electric distribution system, permitting, siting, and analysis (that uses education, outreach, and analysis to help states, regional electric grid operators, and federal agencies develop and improve electricity policies, market mechanisms, state laws, and programs to assist in modernizing the electric grid and the development of new electric infrastructure needed to bring clean energy projects to market), and infrastructure security and energy restoration.
- ➢ 20% (vs. 5% in 2009) increase for the Energy Information Administration to improve energy data and analysis programs.

These numbers are rough, because there are research areas in the basic sciences, which apply across energy source categories, and there are separately very large budgets that are dedicated to high-energy physics and to the maintenance of large experimental facilities in the national laboratories.

Based in large part on the USDOE budget trends, Table 2 very qualitatively summarizes the author's view of the promising energy R&D areas, their potential, foreseen improvements and their time scale, and trends in government funding.

An educational endnote to the US energy budget discussion is that *environmentally* unsustainable 50 years of nuclear weapons production and government-sponsored nuclear energy research results now in annual management and remediation ("cleanup of the environmental legacy") expenditure that is larger than the entire annual energy R&D budget. It consummately demonstrates how past unsustainable activities penalize progress to the future.

6.2. The European Union (EU)

The EU (that is the largest importer and second largest consumer of energy in the world) 7th Framework Programme (2007–2013) had a 50% increase in the energy area (energy, environment, transportation) over the 6th program, and is annually about $1.68 billion plus $0.77 billion for the nuclear research in Euratom [128] for a total of $2.45 billion/year (at 1 Euro = 1.40 US$). Some of the goals for the year 2020 include a 20% reduction of energy use, a 20% share to renewables, and all new coal power plants being of the CCS type. To accomplish this, he EU Commission presented in 2007 a strategic plan to accelerate the development and deployment of cost-effective low-carbon technologies for "fight against climate change, security of energy supply and competitiveness of European companies" with a funding of €3 billion per year [129]. In 2009 they requested €50 billion over the next 10 years, thus tripling the annual allocation. It is noteworthy that individual European countries also have their own energy R&D budgets that in total exceed that of the EU.

6.3. Japan

Japan's energy R&D program was $3.6 billion in 2006 and called for an increase via the "Cool Earth Promotion Programme" of $30 billion in energy and environmental R&D funding over the next five years. 62% of the 2006 budget have been spent on nuclear research, followed by energy conservation and efficiency at 12%, fossil fuels at 9%, renewables at 7%, and power and storage technologies at 3%. It is noteworthy that Japan spent in 2006 roughly 0.083% of its GDP on energy R&D, more than double the proportion of GDP spent by the second highest nation in the category, Finland, about triple that of the United States, and 17-fold that of the EU 6th Framework budget in the same year. [130].

In its report on energy in Japan, the IEA recommended "the development of a more integrated, comprehensive and transparent energy R&D policy framework by explicitly linking national energy

Table 2
A qualitative assessment of promising research directions and their U.S. government funding trend (proposed 2010 annual budget, not including the one-time proposed funding from the American Recovery and Reinvestment Act of 2009).

Direction	Potential	Foreseen improvement	Time scale, years	2010 Government funding trend
Conservation	☆☆☆+	50% of use	Ongoing	☺
Transportation	☆☆☆+	50% of use;120 g CO_2/km by 2012	3–20	☺☺
Hydropower	☆	Reduction of environmental harm	Ongoing	☹☹
Biomass	☆☆+	30% U.S. energy	4–40	☹
Wind	☆☆☆	2.5c/kWh, 15%	1–10	☺☺
Solar PV	☆☆☆+	Competitive price	6+	☺☺
Solar thermal	☆☆	Competitive price	5+	☺
Geothermal (deep)	☆☆	Competiveness	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	7	☺
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	9	☹
Micropower	☆☆☆	Cost, market penetration	7+	☺
Superconductivity	☆☆☆	Order of magnitude	30+	☹☹
Nuclear fission	☆	Manageable wastes, no proliferation	9	☺☺
Nuclear fusion	☆☆☆	Feasibility	35+	☺
Space power	☆☆☆+?	Competitiveness	50+	☹☹

☺: Increased; ☹: decreased; ◯: unchanged.

policy goals with energy R&D priorities through a transparent and long-term strategic research funding roadmap, ensuring that funding is allocated according to a formalised and streamlined process, developing a standard and transparent protocol where funding for and tendering of research proposals are linked to the R&D priorities". Such a recommendation, I note, is valid for most countries' energy R&D policies and plans.

7. Possibly sustainable paths to the future

The first step in any path to the future is wiser use of the energy resources, also referred-to as conservation. 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.

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. These fluctuations are a major impediment to sustainable development. This could be accomplished 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 rapidly put into action. Since large scale carbon sequestration is still impractical, major research, development and testing must be performed in that area.

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.

Buildings are the biggest single contributor to world greenhouse gas emissions. At the same time, improvements are stymied mostly by the fact that energy costs of a building are a very small faction of the resident's/owner's income, who thus have little incentive to implement them. 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 can make a major contribution to this effort. Developing economical "Eco-efficient" or "Living" buildings that not only reduce their negative environmental impact but also help heal and improve the environment is highly encouraged. A broader method is to design residential communities in a way that reduces both indirect use of energy and emissions by reducing the need for transportation and resources by the residents.

At least for this century, 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. 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. [131,132]).

It appears that massive use of nuclear fission power would be stymied unless permanent and economical solutions to the nuclear waste, such as element transmutation, would be attained. This year's decision by the US administration to stop funding for the development of the Yucca Mountain long-term radioactive waste depository is a temporary setback to nuclear power development. Nuclear fusion power could produce a very satisfactory long-term solution, but is still rather far from being achieved.

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. Extra careful sustainability analysis must be applied to the use of biomass for energy, to avert damage to land, water and agriculture and to avoid undue competition with food production. Economical very deep drilling technologies for reaching the enormous geothermal heat resources should be pursued.

R&D to develop commercial superconductors would reduce energy losses significantly, but will take some decades at least. Space power generation for terrestrial use must be explored as a long-term solution.

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, but qualitatively, and based on the current knowledge and situation, they should be to develop effective commercial ways for attaining the sustainable development objectives. It appears that Energy R&D, which is disturbingly small (less than ½% of the energy use value), is based on energy supply. Planning its value and focus on the energy demand is likely to lead to more effective investments.

It is not conceivable that sustainable development can take place without applying reasonable measures for population control.

Sustainability is only emerging as a science, and must be developed and applied urgently to provide analysis and evaluation tools. Included in that is the development of proper metrics and standardize international methods for their definition and measurement. 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. It 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 would not be too late.

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