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Energy resources and use: The present (2008) situation and possible sustainable paths to the future

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ABSTRACT

Recent estimates and forecasts of the oil, gas, and coal resources and their reserve/production ratio, nuclear and renewable energy potential, and energy uses are surveyed. A brief discussion of the status 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 given. 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. Executive summary

1.1. *The current energy resources and consumption situation has generally worsened relative to that at the end of 2006*

A major concern (or opportunity?) is that the price of oil is lately growing very rapidly, from $28 in 2003, to $38/barrel in 2005 and occasionally to above $80 in 2006 and >$145 (so far!). This 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 2007 world primary energy use rose by 2.4%, with the increase rate slightly dropping (Fig. 1), but likely to rise again soon, as the large developing countries in Asia keep improving their standard of living, China's rose by 7.7% (lowest since 2002), India's by 6.8%, US by 1.6%, Japan's dropped by 0.9%, and EU's dropped by 2.2%.

The reserves-to-production ratio (R/P) remains rather constant: ~40 for oil, ~60 for gas, and 200+ for coal, and mostly rising (Figs. 2, 3)! 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 ~16% of world electricity; the number of reactors is increasing very slightly; public perception is improving, new government initiatives started, but the same problems remain.

Renewable energy can satisfy ~2 orders of magnitude more than the world energy demand, but negative impacts aren't inconsequential. Wind and solar PV are experiencing an exponential growth as costs decrease; interest is renewed in solar-thermal power. Strong subsidies for converting food to fuel are increasingly proven to be a mistake, helping triple the price of foods and reducing their availability, and 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 so far 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. Development of traffic management, roads, and public transit are at least as important.

Costing of energy resources remains inequitable, as it doesn't include subsidies, or environmental 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.

The "Living Planet Index" is estimated to have declined since 1970 by about 30%, and the "Ecological Footprint" increased by 70%

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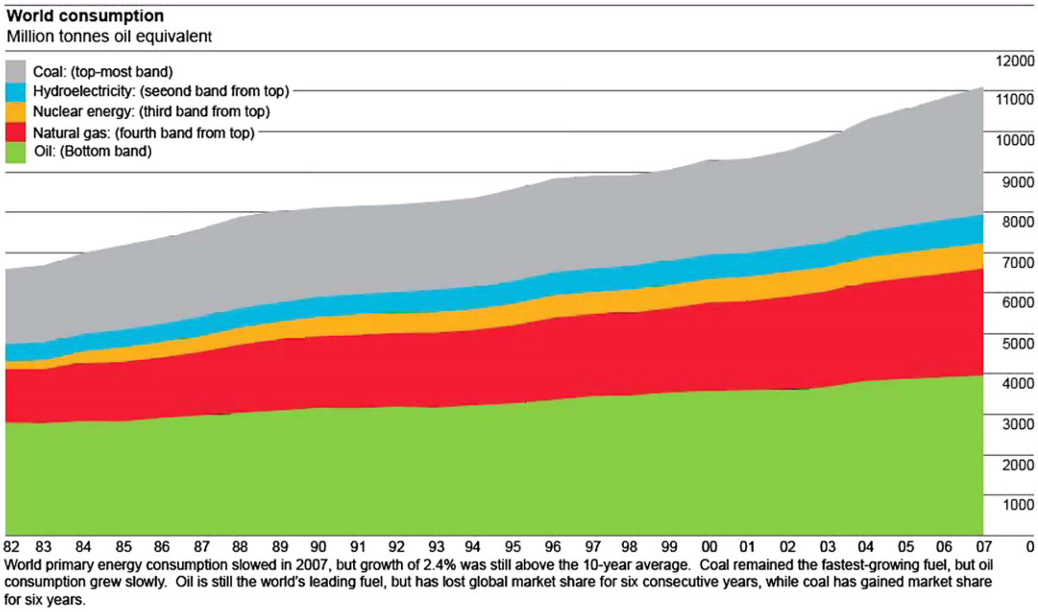

Fig. 1. World primary energy consumption 1981–2007 [1].

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.

1.2. *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

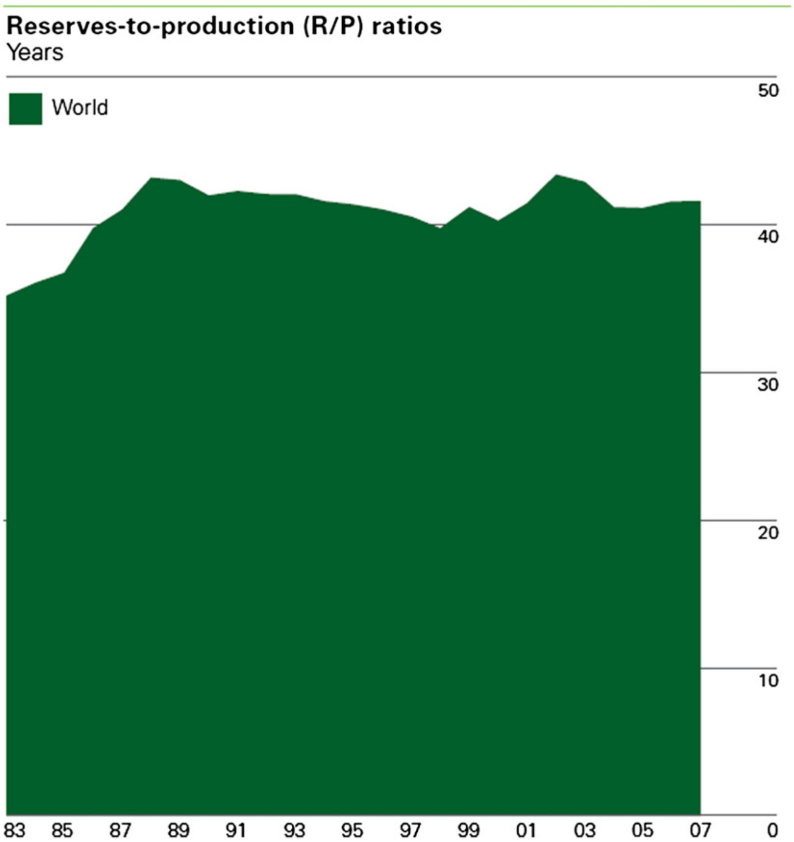

Fig. 2. The oil Reserves-to-Production Ratio (R/P), 1982–2007 [1].

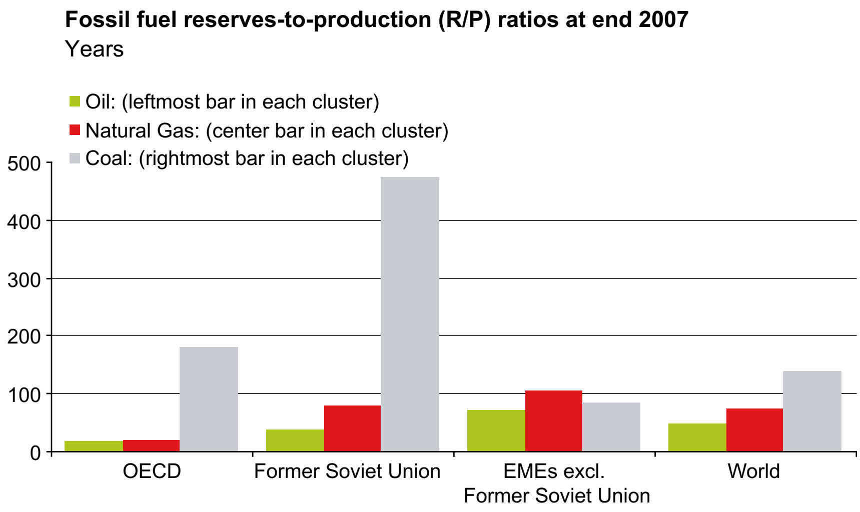

Fig. 3. The fossil fuels Reserves-to-Production Ratio (R/P), 2007 [1].

in the entire 20th century. While the plug-in hybrid electric car and electric-driven public transportation, seem to be the most promising ways towards energy-efficient transport, 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 these plants, partially after conversion to gaseous or even liquid fuels, with the reduced emissions IGCC (Integrated gasification combined cycle) plant receiving major attention. Generally, 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.

Despite the unresolved problems of waste storage, proliferation risk, and to some extent safety, nuclear power plants are likely to be constructed 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 only 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 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.

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, and of their limitations and consequences, and of possible paths to the future, including energy research funding trends, especially in the U.S. The data are taken from many sources, including the latest (June 2008) energy statistics annual report of British Petroleum (BP) for 2007 [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], 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 was published by the author for the situation 6 and 2 years ago [11,12], and this paper updates this very dynamic field.

A 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, use of energy sources that do not produce CO_2, and in methods for CO_2 separation and sequestration. The interest in energy has received another important boost in the last couple of 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. Interest in the energy issue and support for energy R&D are now rising rapidly, abetted by concerns about energy security. The European Union and Japan appear at present to have and afford the most forward-looking and extensive programs, partially because they do not have to bear the enormous relatively recent defense expenses that the U.S. does.

[1] While British Petroleum (BP) has published the Annual Statistical Review of World Energy for 57 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.

3. Sustainable energy development

Energy development is increasingly dominated by major global concerns of over-population, pollution, deforestation, biodiversity loss, and global climate deterioration. For example, more than 20% of the Arctic ice cap has melted away between 1979 and 2003 [13], 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 [14] extended in [15]), 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, increased by 70% in the same period [16]. Whether these reported metrics are absolutely accurate or not, the trends are evident and 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. While the rate of population increase had been dropping since the 2.2%/year peak in 1962 to 1.2%/year currently (Fig. 4), the increase from the current 6.7 billion 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 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 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 having various definitions, we can simply state here that sustainable activities mean that they meet the current needs without destroying the ability of future generations to meet theirs, with a balance among economic, social and environmental needs.

Clearly, quantification of a project's sustainability metrics (indicators) is the first step in sustainable development, design and monitoring, but is very difficult because these are large very complex systems which have technical, ecological, economic and societal components [18]. The modelling 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 embedded in larger systems. Useful work to develop sustainability science is under way but much remains to be done.

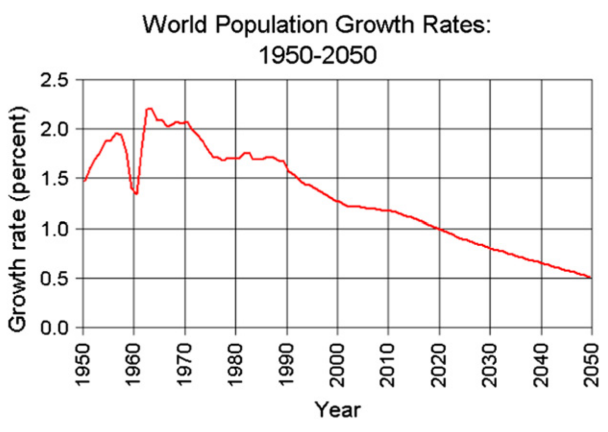

Fig. 4. World population growth rates 1950–2050 [17].

4. Future power generation

4.1. The problem and likely solution trends

The most eminent problem 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]. This translates to the stunning number of one 1000 MW power station brought on line every 3½ days over the next 20 years, on average! All this is even before considering the very likely possibility of massive increase in the use of electric or hybrid vehicles, which would increase the electricity demand proportionally.

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 and 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 for effective attention to other ecological and social problems associated with a coal economy. The reduced emissions IGCC (integrated gasification combined cycle) power plants, increasingly with CO_2 separation, are thus likely to be receiving major attention. Using fossil fuels, the combined cycle 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.

Despite the unresolved problems of waste storage, proliferation risk, and to some extent safety, nuclear power plants are likely to be constructed for special needs, such as 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. At the same time, the amount of uranium-235 in the world is insufficient for satisfying the world energy demand by nuclear energy, a situation that can only change if breeder or natural uranium or thorium reactors are used. The technology for breeders is not, however, safe and mature enough, and is not likely to be in the next couple of decades. The use of breeders and natural uranium reactors also produces plutonium, with the associate safety and proliferation problems. The latter problem, as well as that of nuclear waste storage can be alleviated if transmutation technology is developed to break down the long half-life actinides to shorter half-life elements. Thorium-based reactors are under development, but many problems have to be overcome before commercial units could be built.

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 renewable power generation planning nearly impossible. Costing of energy resources remains inequitable, as it does not include subsidies, environmental, and other consequences. This inequity is usually unfavourable to renewables because fossil and nuclear sources benefit from a long history of major public funds investments into their infrastructure, yet unmatched by investments in renewable energy, and because of the relatively higher stability of renewable energy costs that results in smaller negative impacts on the economy (c.f. [19]).

Wind power generation is typically competitive when oil prices are around \$60/barrel, currently has a respectable worldwide capacity of about 94,000 MWe (~2.5% of the world electric generation capacity of about 4 million MWe) 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. Its widespread use is 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. 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 [20,21], are becoming competitive.

Hydroelectric power provides most of the ~6% contribution of renewable energy to the total energy supply and shows steady but slow growth. Perhaps the most remarkable event is the addition of 18.2 GWe with the Three-Gorges dam in China. The hydro resources are becoming more limited, and construction of such projects poses various environmental, social and security 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 due to vegetation decay.

Biomass energy has the very important benefits of contribution to the security of fuel supply, lower greenhouse gas emissions, and support for agriculture, but there are also some important concerns and obstacles. These include the fact that bioenergy production and policies have mostly not yet 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 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 [22]. Furthermore, there is strong concern about the effects on food production and cost: over the past couple of years corn prices in the US have doubled despite record crops, because of its rapidly increasing use for ethanol production. Filling the 25-gallon (0.094 m^3) tank of an SUV with pure ethanol requires over 450 pounds (204.5 kg) of corn – which contains enough calories to feed one person for a year.

Cellulosic source ethanol may be better but final proof is absent, and conversion demonstrations have only started. There is also a significant interest and effort in producing butanol which is a much better and more transportable fuel than ethanol, and in biodiesel fuels.

It is noteworthy that the biofuels well-to-wheel greenhouse gas abatement potential is not as certain and high as may be thought: less than 20% for corn ethanol, but over 90% for sugar cane based [22]. Furthermore, some recent results have shown that growing plants release methane [23], which has a greenhouse gas potential at least 20-fold that of CO_2.

IEA analyses and projections for biomass uptake by 2030 at competitive costs are 15–150 EJ/yr [9,22]. The proposed research needed for this major progress in using biomass [24] 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, switchgrass).

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. Distributed power generation systems (below about 10 MWe, including even smaller combined heat and power (CHP) systems) very near to the point of use (in some cases in the same building) have an important role because they reduce energy lost in transmitting electricity, especially when the user is far from the main grid, and offer fuel flexibility, often clean and quiet generation, high efficiency in the case of CHP systems, and small-user independence. Development of superconductors that would 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.

4.2. *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 peaked by now, 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 is stated to be the USDOE's primary goal in the fuels program, with a primary objective to develop modules for co-producing hydrogen from coal at prices competitive with crude oil equivalent when integrated with advanced coal power systems (cf. [25]). Development of hydrogen as an energy carrier also sees great activity by other industrialized countries. Despite its advantages in producing near-zero harmful emissions *in the process of its conversion to power*, and the declared plans for its development, 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.

4.3. *Micropower systems (cf. [26,27])*

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. Such systems include miniaturized thermal power cycles, and direct energy conversion systems including fuel cells [28], 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.

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

4.4.1. Fusion

The major appeal of this process for power generation is 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.[2] The radiation from the process is very low and short-lived, but the environmental problems are not negligible. Thus 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 reaction that continuously produces more energy than it consumes. Past predictions of success and commercialization repeatedly had a 25-year target, and those have increased to about 35 years based on the ambitious multi-national ITER program that is constructing a 500 MW fusion test facility in Cadarache, France [29].

4.4.2. Electricity from space? (cf. [30,31])

Power can be produced in space for terrestrial use by using 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 conventional 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.

It is noteworthy that any comparative economical analysis must be conducted on an equitable basis: here specifically including all of the costs of power generation including those of the environmental effects, resource depletion, and embodied energy. Other issues also need to be resolved, some of general nature, such as environmental effects and security and legal aspects, and some system-specific, such as safety of nuclear power plants, and the realization of higher energy conversion and transmission efficiencies.

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. Some recent energy R&D budgets and trends

The information presented here 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. Perhaps a very cogent introduction is the fact that the average government annual expenditure for renewable energy research for all nations is less than $1 per person [22].

The total USDOE budget[3] dedicated to energy R&D was requested to increase in 2009 by about 4%, to about 3.9 b. It additionally has perhaps more than 1 b$ in basic energy sciences (out of the 4.7 b$ USDOE Office of Science budget after its 19% increase, that funds also several other areas which are not directly related to energy). Thus the approximate total requested energy R&D and basic sciences budget is about 5 b$.

The U.S. Department of Energy's National Renewable Energy Laboratory (NREL) had its budget increased by 80% in the past 2 years, to $378 million

Out of the USDOE energy R&D budget part, the programs of energy efficiency and renewable energy, fossil energy, and nuclear energy are about equally budgeted, nuclear having a slight lead. This is a significant change in the apportioning compared with the situation two years earlier, when energy efficiency and renewables had about half of the budget, with the other two areas a quarter each.

The most important budget changes include:

- 19% ($748 million) increase in the DOE's *Science* programs (nuclear physics including major facilities, materials, nanoscience, hydrogen, advanced computing)
- 27% decrease in the *Energy Conservation and Renewable Energy* program (with gains in biomass (+37%), wind, geothermal, and building technologies; drop of 31% in hydrogen.
- 23% increase in the *Fossil Energy* program to $1.13 billion, includes
  - o $648 million for coal carbon capture and storage (CCS) research, includes $149 million for sequestration (It is noteworthy that despite the US administration's refusal to sign the Kyoto 1997 protocol, its stated goal is to reduce greenhouse gas intensity by 18% by 2012,
  - o zero for petroleum and natural gas,
- 84% increase (to $344 million) for the Strategic Petroleum Reserve (capacity expansion from 727 million barrels to 1.0 billion barrels beginning in FY 2008 and later to 1.5 billion barrels).
- $1.65 billion in investment tax credits will accelerate commercial deployment of technologies central to carbon capture and storage.
- Nuclear energy, $1.4 billion, up 37%, including
  - o $302 Million to begin investments in the Global Nuclear Energy Partnership (GNEP), enable an expansion of nuclear power in the U.S. and around the world, promote nuclear

[2] This may no longer be true if plug-in vehicles using lithium batteries become practical and mass-used.

[3] These numbers are very likely to change with the advent of the new U.S. administration in 2009.

non-proliferation goals, and help resolve nuclear waste disposal issues.
  - o $495 Million for permanent geologic storage site for nuclear waste at Yucca Mountain, Nevada, planned for 2017 pending many difficult obstacles.
  - o 3.5-Fold increase (over 2007); $214 million of it for ITER (Fusion) (this is uncertain as of the time of writing).
- 5% increase (to $110.6 million) for the Energy Information Administration to improve energy data and analysis programs.

These numbers are rough, because there are research areas in the basic science that 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.

Japan's energy R&D program is above 2.5 b$ (three quarters of which is for fission and fusion).

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, transport) over the 6th program, and is about 1.75 b$ plus 0.84 b$ for the nuclear research in Euratom. 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. It is noteworthy that individual European countries also have their own energy R&D budgets that in total exceed that of the EU.

Table 1 summarizes 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.

6. Possible 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.

The pursuit of more efficient and less polluting transportation must include not only vehicular improvements (with current 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, ~45%, to world energy and greenhouse-gas emissions. An excellent and practically attainable way to reduce this problem is the design and retrofit of buildings to such that consume less energy (including embodied energy) over their life time, with and without incorporation of renewable energy sources, and further with an extension to "Eco-efficient" buildings that not only reduce their negative environmental impact but also help heal and improve the environment. A broader method is to design residential communities in a way that reduces both indirect use of energy and emissions by diminishing 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. 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. [32,33]). 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. 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 being solar photovoltaics and thermal power, wind, and to some extent biomass. Very deep drilling, or generally access, technologies for reaching the enormous renewable 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 above-described objectives.

Sustainability is only emerging as a science, and must be developed and applied urgently to provide analysis and evaluation tools. It is of immediate importance because energy conversion and

Table 1
A qualitative assessment of promising research directions and their current U.S. government funding trend (valid for the beginning of 2008).

Direction	Potential	Foreseen improvement	Time scale, years	2009 Government funding trend
Conservation	☆☆☆+	50% of use	Ongoing	☹☹
Transportation	☆☆☆+	50% of use; 120 g CO_2/km by 2012	3–20	☹
Biomass	☆☆+	30% U.S. energy	4–40	☺☺☺
Wind	☆☆☆	2.5c/kWh, 15%	1–15	☺
Solar PV	☆☆☆+	Competitive price	6+	☺☺
Solar thermal	☆☆	Competitive price	5+	☹
Geothermal (deep)	☆☆	Competitiveness	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	☺
Global warming/CO_2	☆☆	~0 CO_2	10–15	☺☺
Fuel cells	☆+	60%+; price	9	☹
Superconductivity	☆☆☆	Order of magnitude	30+	☹☹
Nuclear fission	☆	Manageable wasters, no proliferation	9	☺☺
Nuclear fusion	☆☆☆	Feasibility	25+	☺
Micropower	☆☆☆	Cost, market penetration	7+	☺☺
Space power	☆☆☆+?	Competitiveness	50+	☹☹

Increased, ☺; decreased, ☹.

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 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.

References

[1] British Petroleum. Statistical review of world energy 2008. Available from: <http://www.bp.com/productlanding.do?categoryId=6929&contentId=7044622> [accessed 7/31/2008].

[2] U.S.D.O.E. Available from: <http://www.energy.gov/> [accessed 7/31/2008].

[3] U.S.D.O.E. Energy information administration. Available from: <http://www.eia.doe.gov/> [accessed 7/31/2008].

[4] U.S.D.O.E. Office of Management, Budget, and Evaluation (MBE). Office of Budget, Available from: <http://www.cfo.doe.gov/crorg/cf30.htm> [accessed 7/31/2008].

[5] U.S.D.O.E. Energy efficiency and renewable energy. Available from: <http://www.eere.energy.gov/> [accessed 7/31/2008].

[6] USDOE Office of Fossil Energy. Available from: <http://www.fossil.energy.gov> [accessed 7/31/2008].

[7] National Renewable Energy Laboratory. Available from: <http://www.nrel.gov/> [accessed 7/31/2008].

[8] The European Commission website on Energy Research. Available from: <http://europa.eu.int/comm/research/energy/index_en.html> [accessed 7/31/2008].

[9] International Energy Agency. Available from: <http://www.iea.org/> [accessed 7/31/2008].

[10] International Atomic Energy Agency. Available from: <http://www.iaea.org/> and <http://www.iaea.org/programmes/a2/index.html> [accessed 7/31/2008].

[11] Lior N. The state and perspectives of research in the energy field, invited keynote paper. In: Ulgiati S, editor. The third international biennial workshop, Advances in energy studies: reconsidering the importance of energy. Italy: Porto Venere; 24–28 September 2002. p. 351–64.

[12] Lior N. Energy resources and use: the present situation and possible paths to the future. Invited keynote lecture, PRES 06 (9th Conference "Process integration, modeling and optimisation for energy saving and pollution reduction"), joint with CHISA 2006 (17th International Congress of Chemical and Process Engineering), Praha, Czech Republic, August 2006. Energy 2008;33:842–57. in revised form.

[13] NASA. <http://www.nasa.gov/centers/goddard/news/topstory/2003/1023esuice.html> [accessed 7/31/2008].

[14] Wackernagel M, Rees W. Our ecological footprints. Gabriola Island, BC, Canada: New Society Publishers; 1996.

[15] Nguyen H, Yamamoto R. Modification of ecological footprint evaluation method to include non-renewable resource consumption using thermodynamic approach. Resources, Conservation and Recycling 2007;51:870–84.

[16] WWF (World Wildlife Federation; World Wide Fund For Nature). The Living Planet. Available from: <http://www.panda.org/news_facts/publications/living_planet_report/lp_2006/index.cfm> [accessed 7/31/2008].

[17] The U.S. Census Bureau. Available from: <http://www.census.gov/ipc/www/idb/worldpopinfo.html> [accessed 7/31/2008].

[18] Lior N. About sustainability metrics for energy development, invited keynote presentation at the 6th Biennial International Workshop, Advances in energy studies, Graz, Austria. Graz University of Technology Publication, ISBN 978-3-85125-018-3; 29 June–2 July 2008. 390–401.

[19] Awerbuch S, Sauter R. Exploiting the oil – GDP effect to support renewables deployment. Energy Policy 2006;34(17).

[20] Lior N. Solar energy and the steam Rankine cycle for driving and assisting heat pumps in heating and cooling modes. Energy Conversion 1977;16(3):111–23.

[21] Koai K, Lior N, Yeh H. Performance analysis of a solar-powered/fuel-assisted Rankine cycle with a novel 30 hp turbine. Solar Energy 1984;32:753–64.

[22] Dixon RK, Sims RE. IEA Secretariat perspectives on bioenergy, presentation at the international renewable energy alliance meeting "100% Renewable Energy Mix Scenarios for Africa and Asia", Hon. Peter Rae, Chair, United Nations, NY; 7 May 2007. Available from: <http://www.iea.org/RDD/> Data from the International Energy Agency [accessed 7/31/2008].

[23] Keppler F, Hamilton JG, Brass M, Rockmann T. Methane emissions from terrestrial plants under aerobic conditions. Nature 12 January 2006;439:187–91.

[24] USDOE. The biobased materials and bioenergy vision. Draft; 18 July 2001. Available from: <http://www1.eere.energy.gov/biomass/pdfs/final_2006_vision.pdf-1355.5KB> [accessed 7/31/2008].

[25] USDOE Office of Fossil Energy Vision 21 program. Available from: <http://www.fossil.energy.gov/programs/powersystems/vision21/index.html> [accessed 7/31/2008].

[26] Majumdar A, Tien CL. Micro power devices. Microscale Thermophys Eng 1998;2:67–9.

[27] Kribus A. Thermal integral micro-generation systems for solar and conventional use. ASME J Solar Energy Eng 2002;124:180–97.

[28] Jamelyn D, Jones Evan O, Phelps Holladay Max. Hu Soc Opt Eng 2002;4559:148–56 [Jianli, High-efficiency microscale power using a fuel processor and fuel cell, Proc SPIE Int].

[29] USDOE Department of Science. . Available from: <http://www.science.doe.gov/News_Information/News_Room/2006/ITER/index.htm> [accessed 7/31/2008].

[30] Glaser PE, Davidson FP, Csigi KI, editors. Solar power satellites, the emerging energy option. New York: Ellis Horwood; 1993.

[31] Lior N. Power from space. Energy Convers Manage J 2001;42(15–17):1769–805.

[32] Herring H. Energy efficiency—a critical view. Energy 2006;31:10–20.

[33] Sorrell S, Dimitropoulos J. The rebound effect: microeconomic definitions, limitations and extensions. Ecol Econ 2008;65:636–49.