Available online at www.sciencedirect.com
ScienceDirect
ELSEVIER
Energy 33 (2008) 842–857
ENERGY
www.elsevier.com/locate/energy

Review

Energy resources and use: The present situation and possible paths to the future ☆

Noam Lior*

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

Received 24 February 2007

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. The impact of the rapidly growing economies of the highly populated countries, as well as of the concern about global warming, are presented and assessed. A brief discussion of the status and prospects of fossil, nuclear and renewable energy use, and of power generation (including hydrogen, fuel cells, micro power systems, and the futuristic concept of generating power in space for terrestrial use, is given. A brief summary of the energy research effort and budgets in the US, and EU are presented, and 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 research and development (R&D) areas, their potential, foreseen improvements and their time scale, and last year's trends in government funding are presented.

Keywords: Energy assessment; Power generation; Energy forecast; Sustainability

Contents

☆This is a review-based revision of the invited Plenary Lecture and paper with the same title, given at the PRES '06 (Ninth Conference on "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.

*Fax: +1 215 573 6334.
E-mail address: lior@seas.upenn.edu

0360-5442/$ - see front matter
doi:10.1016/j.energy.2007.09.009

1. Executive summary: the current energy resources and consumption situation

1.1. Despite the difficult problems with energy, there are some "good news"

- World primary energy consumption increased by "only" 2.7% in 2005, below the 2004 strong growth of 4.4%: largest in Asia Pacific region, 5.8%, weakest in North America at 0.3%.
- The US and EU consumption fell slightly, while China accounted for more than half of global energy consumption growth.
- Although 2005 was the third consecutive year of rising energy prices, real oil prices remained below the peak of the early 1980s.
- There has been no physical shortage of coal, oil or gas.
- So far, the international economy has proved surprisingly resilient to higher energy prices and continued to grow.
- The "energy intensity" (energy consumption per $ GDP) continued dropping for both the OECD and other country groups.
- Global proved reserves of oil and gas have continued to increase.

1.2. The current energy resources and consumption situation

- The rate of increase in total world energy use is slightly dropping, but it is likely to change soon, as the large developing countries in Asia keep improving their standard of living.
- The resources-to-production ratio (R/P) for oil ≈ 40, for gas ≈ 60, for coal $= 200+$, and is mostly rising! There will probably be sufficient oil and gas for this century, and coal for 2 or more.
- Nuclear power produces $\sim 16\%$ of world electricity; while the amount of nuclear power is increasing, 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 are not inconsequential. Wind and solar photovoltaic (PV) power generation are experiencing an exponential growth as costs decrease, and is becoming commercially competitive.
- Hydrogen production efficiency is low, and problems of transport and safety remain.
- A major concern (or opportunity for renewable energy?) is that the price of oil is lately growing very rapidly, from $28 in 2003, to $38/barrel in 2005 and to above $70 (so far!) in 2006.
- Costing of energy resources is inequitable, as it does not include subsidies, environmental, and other consequences.
- Sustainability is only emerging as a science, and must be developed and applied urgently.

1.3. Future power generation

- The most eminent 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.
- 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, with the reduced emissions integrated gasification combined cycle (IGCC) plant receiving major attention; since it produces the highest amounts of CO_2 per unit useful heat, its use would increasingly have to be accompanied

by CO_2 separation and sequestration, technologies, which are not commercially mature yet.

- 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 countries that have much better access to uranium than to fossil fuels. The amount of uranium 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.
- PV 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.
- The investments in energy research and development (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 possible paths to the future, including energy research funding trends, especially in the US. The actual data are taken from many sources, including the excellent web sites of the US Department of Energy (USDOE) [1], its Energy Information Administration [2], Office of Budget [3], Office of Energy Conservation and Renewable Energy [4], Office of Fossil Energy [5] and the National Renewable Energy Laboratory [6], from the Energy Research web site of the EU [7], the International Energy Agency [8] and the energy statistic annual report of British Petroleum (BP) [9]. The analysis, interpretation, and comments are entirely the author's and do not represent any institutional or government views. A review of similar nature was published by the author 5 years ago [10], and this paper updates this very dynamic field.

The decade following 1973 has seen exponential growth in interest, R&D, and government as well as industry support of energy research. In fact, it has sometimes appeared that the amount of money and effort exceeded both the number of available experts and the number and quality of the ideas to which they were allocated. The growth was spurred from the grass roots due to quasi-scientific predictions of imminent depletion of fluid fuels resources by the very beginning of the 21st century, and by anxiety of dependence on hostile and unreliable oil suppliers. The sense of urgency in energy research diminished from the late 1980s because of successful energy conservation improvements, relatively low fluid fossil fuel prices, reasonable reliability of the fossil fuel supply, and assessments of availability of fossil fuels until late in this century. There indeed was also some sense of disappointment that the enthusiasm and expenditures of the 1970s and 1980s did not meet the somewhat unrealistic expectations, such as independence from oil by the mid 1980s and widespread use of renewable energy. These, accompanied by the election of governments with a drastically different political philosophy, have resulted in sharp reductions in energy R&D budgets, which were literally decimated for alternative energy resources, from solar to nuclear, especially in the US.

This decline has been somewhat arrested toward the end of the 1990s, primarily due to increasing concerns about global warming, caused primarily by increasing emissions of CO_2 due to 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. While not at the earlier levels, interest in the energy issue and support for energy R&D are on the rise, abetted by concerns about energy security.

3. Sustainable energy

Energy development is increasingly dominated by major global concerns of over-population, air pollution, fresh water pollution, coastal pollution, deforestation, biodiversity loss, and global climate deterioration. 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.

Any effort to render activities sustainable immediately invokes the need to establish quantitative sustainability criteria. In the energy field, for example, they go well beyond the conventional energy (or exergy) or economic indicators such as production consumption, conversion efficiencies, and costs. They must include social, political, and ecological considerations, both short and long term, which are typically very difficult to quantify, and performance depends on the country, and even the community to which they are to be applied. The planning and design of sustainable systems is much more complex and difficult than conventional planning and design that does not include the rigorous investigation of sustainable approaches, because the addition of the many interdisciplinary and probabilistic multi-objective sustainability criteria are added to the generally deterministic process of system modeling, analysis, optimization, and selection. Briefly, this highly complex system is the objective of sustainability science, which is still in its infancy and should thus be developed thoroughly soon. One example of a good start is the five-agency international effort to develop appropriate guidelines and methodologies [11,12].

4. The 2006 world energy status summary

4.1. The current energy consumption and resources situation (some from [9])

The world primary energy consumption increased by 2.7% in 2005, below the 2004 strong growth of 4.4% (Fig. 1). It was largest in the Asia Pacific region, 5.8%, and weakest in North America at 0.3%. In the US and EU, consumption fell slightly, while China accounted for more than half of global energy consumption growth. At the same time, there have been no physical shortages of coal, oil or gas (with some minor and temporary local exceptions). This slight reduction in global energy consumption increase rate in 2005 is likely to change soon, as the highly populated developing countries in Asia keep improving their standard of living.

A major concern is that the price of oil is lately growing very rapidly, from $28/barrel in 2003, to $38 in 2005 and to above $70 in 2006, yet although 2005 was the third consecutive year of rising energy prices, real oil prices remained below the peak of the early 1980s. It is also noteworthy that, so far, the international economy has proved surprisingly resilient to higher energy prices and continued to grow. It is noteworthy that the energy intensity (energy consumption per $ GDP) continued dropping for both the OECD and other country groups [13].

Nuclear is the other major non-renewable source of energy, mostly electric power, which produces ~16% of world electricity [14]. While the amount of nuclear power is increasing, the number of reactors is increasing very slightly: counting the reactors placed on line and deducting those that were retired, only 4 new reactors were added in the 3-year period of 2004–2006. Because of the increasing concern with global warming generated from the use of

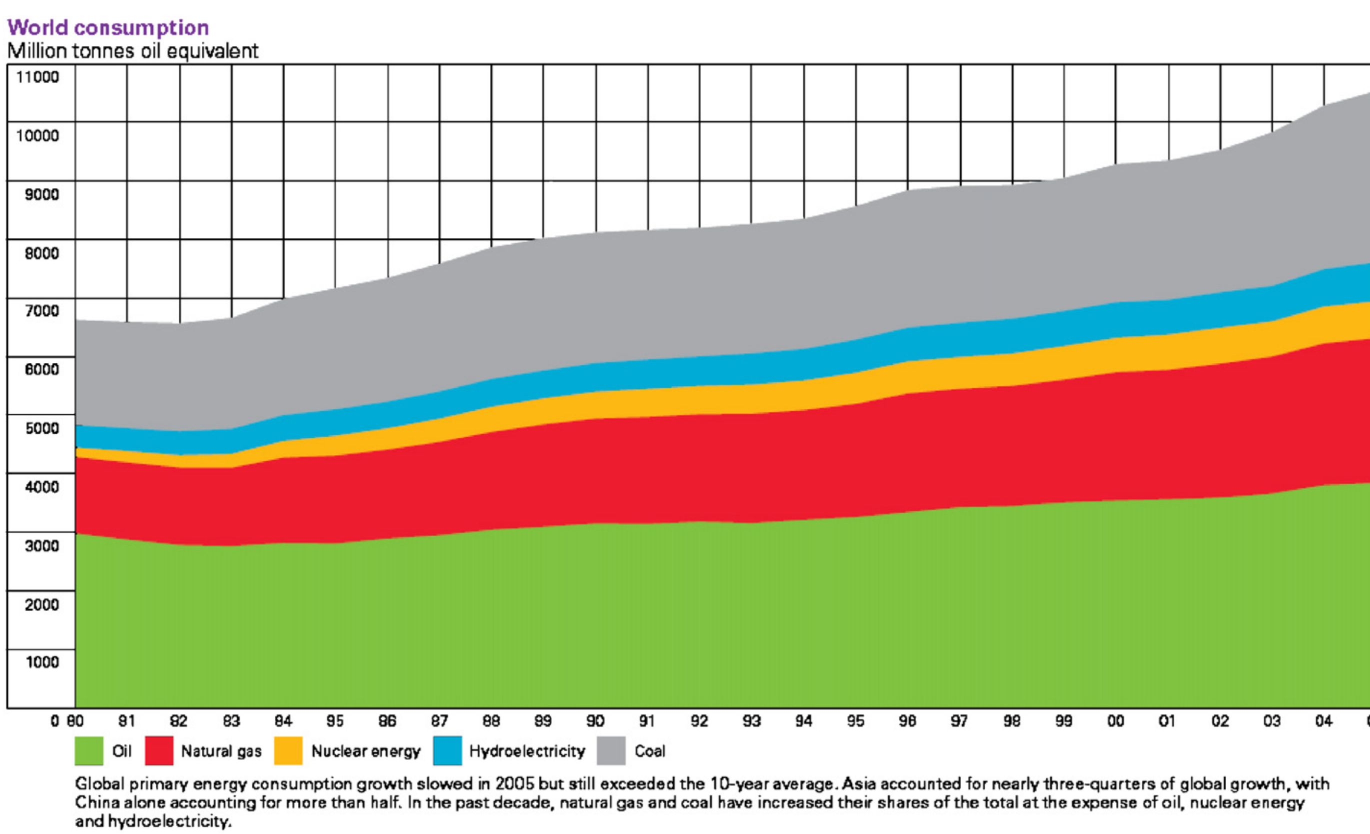

Fig. 1. World consumption of primary energy, 2005 [9].

fossil fuels, and because no serious nuclear accidents have occurred during the past 20 years, public perception is improving, new government initiatives started, but the same old concerns about safety and nuclear waste remain, augmented by more recently increased concern about nuclear proliferation.

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, 90% of it by hydro.

4.2. 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 $\frac{1}{2}$ of world and 1/8 of people in the OECD countries [15]. Mostly coal is used, at electricity production efficiencies much lower than those of the world. The current electricity shortage is somewhat larger than 35 GW. 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 is demonstrated by the fact that the average annual primary energy consumption growth jumped by 15.3% during the 3-year period of 2002–2004 from the 3.4% during the entire 11-year period 1990–2001. Similarly for the same periods, the annual electricity consumption jumped by 15.7% over the 3 years, from 8.4% over the previous 11 years (Table 1).

This 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% [15].

4.3. Energy conservation

The energy use trends shown in Fig. 1 could, and should, of course be reduced by more judicious consumption.

Table 1
Electric power capacity changes in China [15]

Year	Capacity/GW			
	Total	Thermal	Hydro	Nuclear
1980	66	45.6	20.3	–
1985	87	60.6	26.4	–
1990	139	101.8	36.0	–
1995	217	162.9	52.2	2.1
2000	319	237.5	79.4	2.1
2004	441	325	108	6

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. For example, even modest and voluntary savings measures by the OECD countries over the 3-year period 2005–2007 were predicted to reduce the fuels consumption growth by about 20% [16]. A study by the US EIA [17] has predicted that implementation of a rather mild energy conservation policy, consisting of a set of measures including modest tax incentives, voluntary standards, a more rigorous enforcement of the current government recommended Corporate Average Fuel Economy (CAFE) requirements to be phased-in between 2008 and 2012, and implementation of an energy efficiency performance standard (EEPS) for natural gas and electricity suppliers in five States to reduce growth in their customers' energy use by 0.75% per year from 2009 to 2025, would result by the year 2025 in a 2.9% reduction of the energy consumption compared with the scenario that does not employ these conservation measures. A somewhat more strict set of measures, which adds among other things a requirement that the electric and natural gas industries increase their energy efficiency from 2006 to 2016 by 5%, was forecast to reduce the energy consumption by the year 2025 by 7%. The latter results in an overall energy consumption increase of 20% relative to the year 2005 value, proportionally smaller than the 30% forecast increase without any conservation measures.

4.4. Fossil fuel energy

An interesting global phenomenon is that despite the rise in consumption of fossil fuels, the quantities of proven reserves rises 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 150 for coal (Fig. 2). Although it is hard to know what the actual quality of the resources data is, one reason, but perhaps not the only one, is that exploration and beneficiation of fuels increase with consumption and with price.

Oil, gas, and coal are transported massively both inside countries and internationally, via all means of land and water transportation. This has many 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 [18]. It is extremely worrisome therefore, that insufficient funds are dedicated (by both governments and industry) to modernization and improvements of these distribution systems, and, for example, these areas were taken out of this year's USDOE budget.

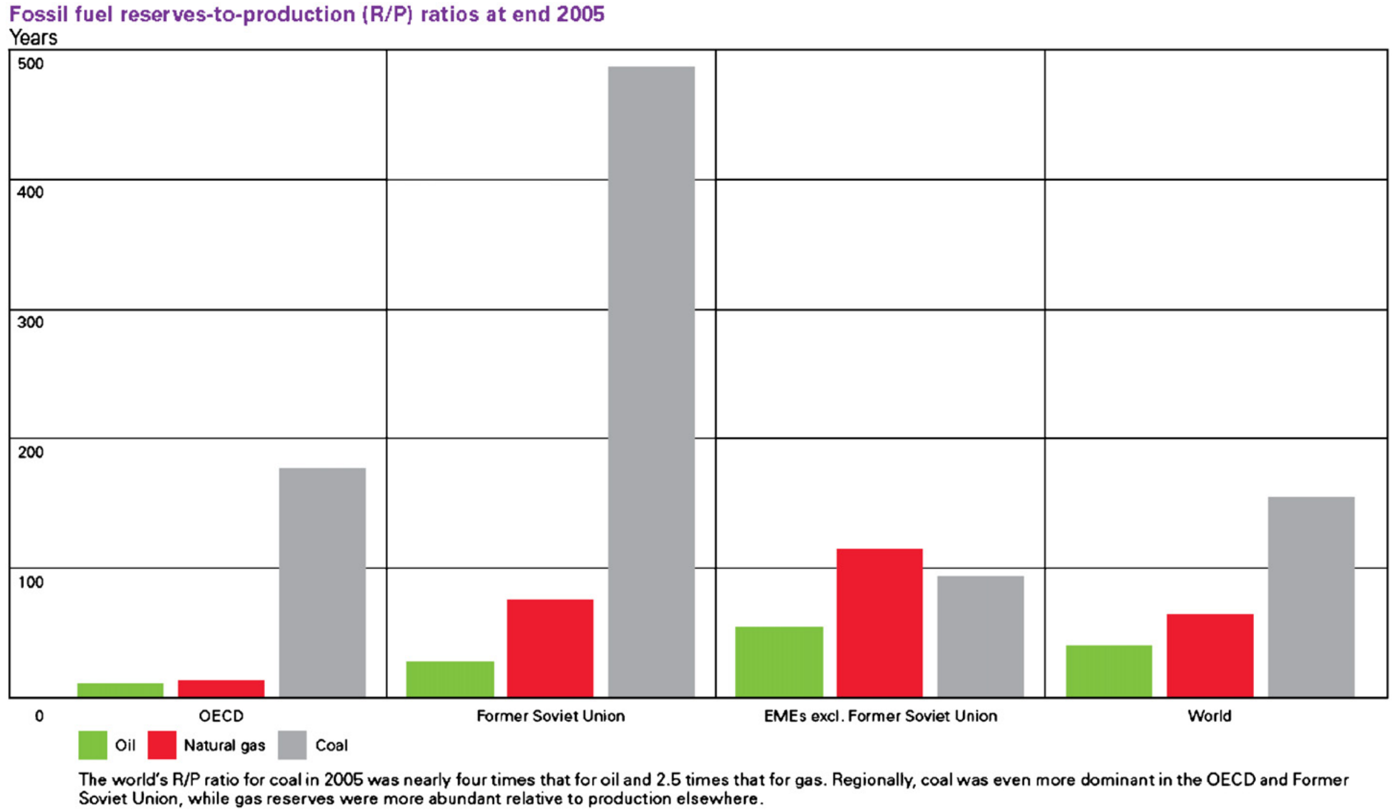

Fig. 2. The world's reserves/production (R/P) ratios [9].

Some forward-looking oil/gas companies have taken the CO_2 global warming problem as a business opportunity in making efforts to enable favorable fuel switches, increasing energy efficiency, supporting the development of renewable energy systems as well as hydrogen production and handling. Statoil, for example, is particularly interested in developing a business from CO_2 capture and storage since 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 [19]. 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.

4.5. Nuclear power

It is noteworthy 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. As of June 2006, there were 442 nuclear power plants in operation with a total net installed capacity of 370 GW(e) (4 more than in 2002), 6 nuclear power plants are in long-term shutdown, and 29 nuclear power plants are under construction [14].

While the use of nuclear power alleviates the global warming problem significantly (especially if electricity or hydrogen produce by nuclear means is also used for transportation), some of the leading problems associated with generating nuclear power have not gone away. For example, the DOE reported that as of December 2005 the US accumulated about 53,440 tons of spent nuclear fuel from nuclear reactors [20,21], and it is estimated it has at least 250,000 tons civilian nuclear waste, much more military [22] (estimated to be 4–5 fold more [23]), including at least 1500 tons plutonium [24], and that there are 200 million tons of low-level waste from uranium milling, at mine sites (cf. [23], mostly based on public US government sources). Many other countries also have large amounts of such wastes (just the spent fuel in 1999 was estimated to be 220,000 tons worldwide [25]), 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 [26,27] (with a target date of 2030) that would have the following main attributes: electricity price competitive with that generated by natural gas power plants (3c/kWh), capital cost of $1000/kW, construction time of 3–4 years, and demonstrated safety to regulatory agencies and to the public. The safety attributes would include reactor cores that do not melt in an accident, coolants that do not react (corrosion and other chemical reactions) with their conduits, passive cooling (i.e. typically driven by the natural buoyancy of the coolant rather than by pumps and fans, which are instead, no accident scenarios that require offsite emergency response, and high tolerance to human error. Nuclear waste problems would be partially addressed by accounting from the outset for the full fuel cycle from mining to plant decommissioning, by complete solution for all waste streams, and minimization of produced waste. The proliferation risk is to be reduced through appropriate choice of materials, management, and construction. These goals are positive but appear to be unachievable in that time frame without huge investments, which, if made, would diminish other energy development efforts.

Geological storage of high level nuclear wastes is facing strong public opposition, particularly because of the extremely long time, of the order of tens of thousands of years, needed for its surveillance and monitoring. A more reasonable method of dealing with this problem, if commercially feasible, is partitioning and transmutation of the long-life radioactive elements (cf. [25,28–31]), 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. 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 very abundant element in nature (cf. [30,31]). The released energy for a given quantity of natural element is more than 100 times greater than the one in the case of the currently used U-235-driven nuclear reaction. The ultimate wastes of the fission reaction are primarily the fission fragments, which remain dangerously radioactive for only hundreds of years, as well as a small amount of actinides that can be used as new fuel and are very difficult to serve as weapons. Since these reactions need about twice as many neutrons as U-235 fission, it is proposed that neutrons produced by a high-energy proton beam hitting a spallation target be supplied externally. The cost and energy penalty of this approach need further attention.

In the meantime, efforts are under way to extend the life of current plants from the originally planned 40 to 60 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}/reactor-year), of nuclear wastes, and of use for warfare and terrorism. According to some opinions, ''the choice is between the plague and cholera'' [32].

4.6. Renewable energies

Renewable energy can supply the world's foreseen energy needs many fold as can be seen in Table 2, but, with the exception of hydropower, geothermal, some forms of biomass, and wind, further development is necessary to make renewable energies cost competitive. As prefaced in Section 4.1, renewable sources account for about 3% of the total energy use, but about 18% of the total electricity, with hydropower accounting for almost 90% of this 18%.

4.6.1. Hydroelectric power

There is steady slow growth in hydroelectric power, perhaps the most remarkable event being the forthcoming addition of 18.2 GWe with the Three-Gorges dam in China in 2009. Construction of such projects poses various environmental and social problems; this dam, for example, creates 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.

4.6.2. Solar thermal

This includes heating, process heat, and solar thermal power generation. An example of solar heating is a project in which we were assessing the possibility of mass installation of solar space and water heaters in Philadelphia on the roofs of row-home, a type of building that constitutes about 70% of residential urban housing in eastern and central US [34,35]. The test and demonstration building system shown in Fig. 3 operated reliably for about 20 years (when needed, and could have operated longer if the house roof did not need unrelated repairs).

Solar thermal power generation had a remarkable success in the hybrid solar–fuel plants using trough concentrators (originally installed by the Luz company), whch produce nearly 1 GW electricity competitively (though with some tax benefits) in California, at a construction cost of $3000/kW (Fig. 4). The basic concepts for such hybrid systems were studies both theoretically and experimentally by us (including the development of a novel turbine [36], Fig. 5) much earlier under USDOE sponsorship, showing that the investment of about 25% high-temperature energy, generated by combustion or solar

Table 2
World renewable energy use (1998) and technical potential [33,37]

	Supply in 1998, EJ	Technical potential, EJ/year
Biomass	45±10	200–500
Wind	0.07	70–180
Solar	0.06	1500–50,000
Hydro	9.3	50
Geothermal	1.8	5000
Marine	–	n.e.

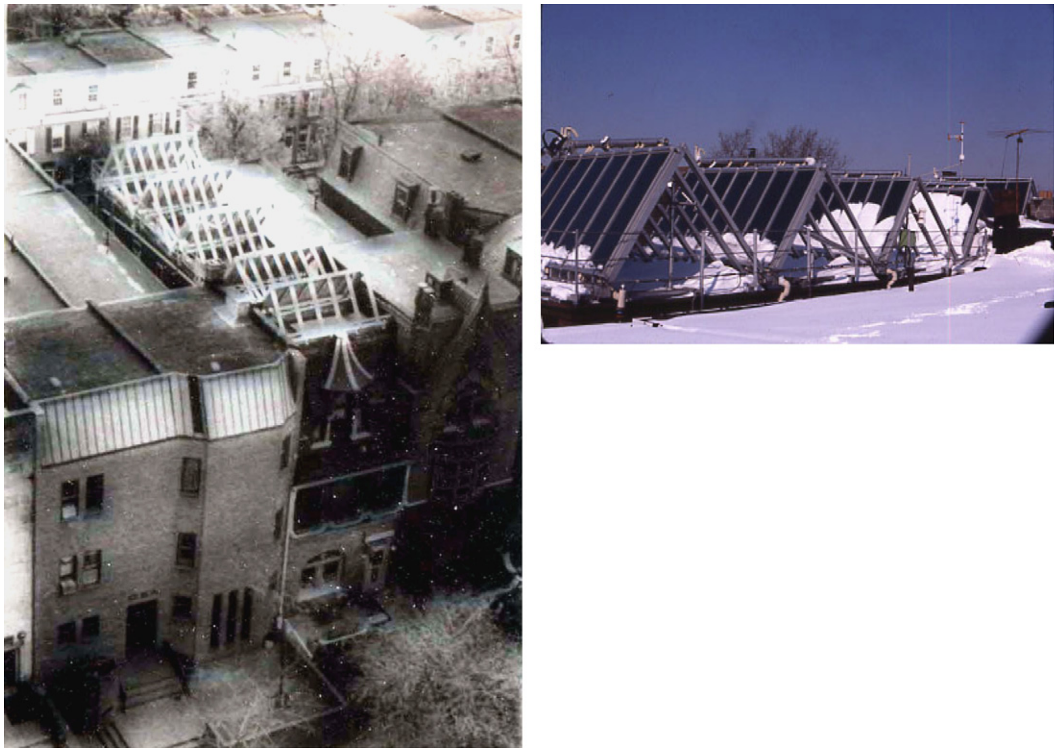

Fig. 3. "SolaRow", the University of Pennsylvania solar row home, the first solar-heated house in Philadelphia, Pennsylvania, USA, 1976 [34,35].

Fig. 4. About 1000 MW of electricity are produced in the California desert at competitive prices by parabolic trough solar concentrators, assisted by fuel, at a capital cost of about $3000/kW.

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.

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.

4.6.3. Solar photovoltaic [37–39]

About 5000 MW PV power is installed nowadays, and it experiences exponential growth, 31% a year on the average over the past decade. 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, which would allow much easier installation even on surfaces that are curved. Large R&D programmes are underway OECD countries, with Japan dominating, and recently a US laboratory announced the first development of cells with an efficiency reaching 40.3% [40].

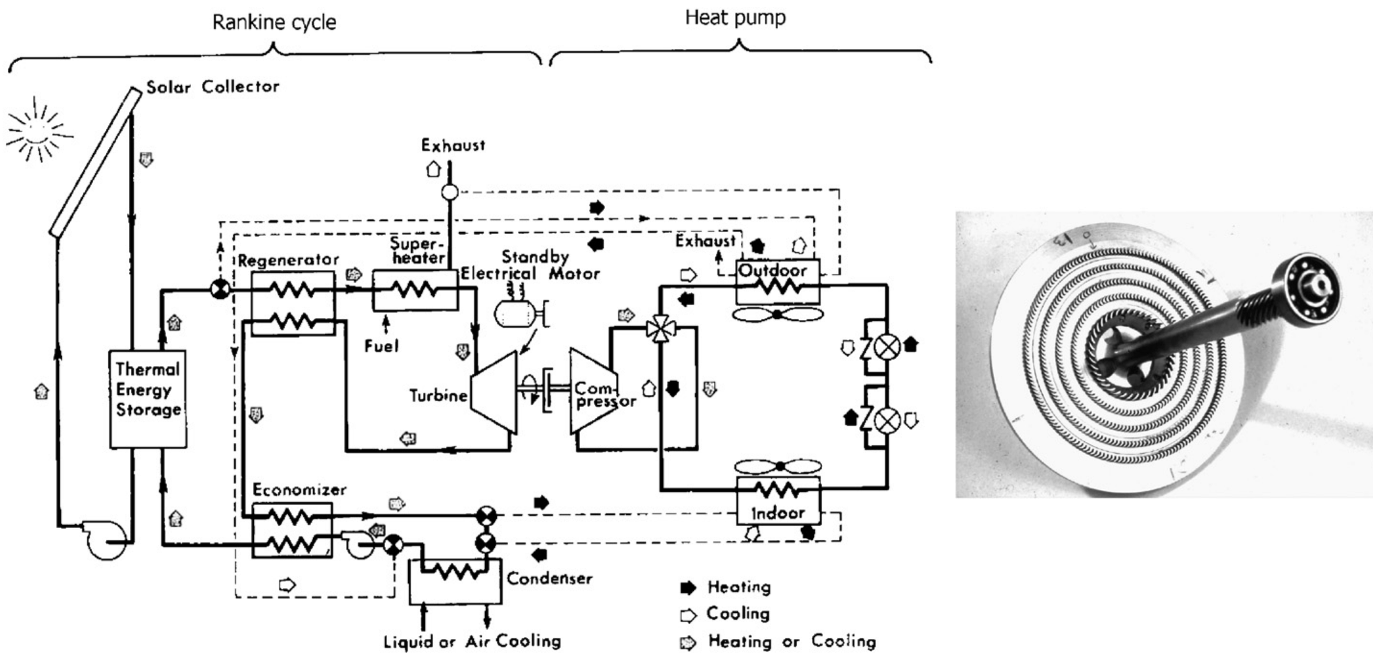

Fig. 5. "SSPRE", the solar-steam-powered Rankine engine, a hybrid solar-powered fuel-assisted system, with the 30 HP turbine developed for it [36].

The cost of PV systems is high, of the order of $5000/kW, 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 expected to drop back to the earlier prices once new manufacturing factories come on line.

4.6.4. Wind energy

Wind power progress is remarkably successful, with a capacity increase of about 15 GW electricity in 2006 [41], forecasted to rise to an increase of 29 GW/year by the year 2014 [42]. For example, "Wind Force 12" [43] 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.

The wind power systems are increasingly efficient, reliable, and big, with 5 MW turbines reaching a diameter of 125 m and height of 90 m. There is great interest in developing 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. Some operating offshore and onshore systems are shown in Fig. 6.

Barriers limiting or emerging for the future development of large deployment of wind power are [42]:

- Economy of technology, in which it was found that the "learning curve" (rate of annual cost reduction due to improved design, construction, and operation) is 15–20%;
- Market incentives allocated by government for replacing unsustainable and polluting power sources by wind energy;
- Efficiency of the electricity market and grid, primarily to accommodate the fact that wind energy is intermittent and distributed;
- Planning and environmental impact (noise, visual, and wildlife).

4.6.5. Biomass energy

While use of biomass has the very important benefits of contribution to the security of fuel supply (some of the conversion paths and their efficiencies and cost estimates are listed in Table 3), lower greenhouse gas emissions (although some recent results have shown that growing plants release methane [44]), 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 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 [45].

Fig. 6. Wind power. Left: offshore turbines, 40 MW, Middlegrunden, Denmark; Right: onshore wind farm, 630 MW, Palm Springs, California, USA.

Table 3
Some biomass conversion routes to fuel [33,37]

	RME	Ethanol from sugar or starch crops	Ethanol from woody biomass	Hydrogen from woody biomass	Methanol from woody biomass	Bio-oil from woody biomass
Concept	Extraction and esterification	Fermentation	Hydrolysis, fermentation and electricity production	Gasification	Gasification	Flash pyrolysis
Net efficiency of energy conversion	75% (based on all energy inputs)	50% for sugar beet; 44% for sugar cane	60–70% (longer term, with power generation)	55–65%, –>60–70% (longer term)	50-60%, –>60–70% (longer term)	70% (raw bio-oil)
Cost range, short term	15–25	15–25 S/GJ for sugar beet; 8–10	10–15	8–10	11–13	n.a.
Cost range, long term	n.a.	n.a.	6–7	6–8	7–10	Unclear

Cellulosic source ethanol may be better but final proof is absent.

5. Future power generation

5.1. The problem and likely solution trends

The most eminent problem is that expected demand for electricity would require during the coming 2 decades the installation of as much power generation capacity as was installed in the entire 20th century [2]. This translates to the stunning number of one 1000 MW power station brought on line every $3\frac{1}{2}$ 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 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. The extensive use of coal will increase the need for more stringent emissions controls and other ecological and social problems associated with a coal economy. The reduced emissions IGCC 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 in countries that have much better access to uranium than to fossil fuels. The amount of uranium in the world is insufficient for satisfying the world energy demand by nuclear energy, which can only change if breeder 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. In view of the important potential contribution of the use of nuclear power to reduce global warming, accelerated R&D on the type of reactors with the targeted attributes of “Generation IV”, on advanced breeder fuel systems, such as thorium, on transmutation of long-term radioactive wastes, and on severing the connection between nuclear power generation and possible weapons proliferation, should be encouraged.

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. PV 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 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 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.

5.2. 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 using also fossil fuels. Various important technical issues must be resolved before fuel cells attain significant market penetration, the cost must be reduced by an order of magnitude, and 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. [46]). Development of hydrogen as an energy carrier also sees great activity by other industrialized countries. Despite its advantages in producing near-zero harmful emissions, 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 (with the concommitant environmental effects) for its production, and issues of safety, storage, and distribution.

5.3. Micro power systems (cf. [47–52])

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 [53], 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 recall an analogy that 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.

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.

The above-described devices are different from what in the industry are called "microturbines", ("personal turbines") that are small relative to conventional systems, of the size of a domestic refrigerator, produce of the order of 30–100 kWe operating on gas, oil, or biogas at an efficiency of 30% at best, and have emissions of NO_x and CO below 10 ppm, which are being increasingly introduced to the market for distributed generation, for homes and commercial applications [54]. Studies of combining such microturbines with solid oxide fuel cells indicate the possibility of reaching efficiencies of 60% [55–57].

5.4. Electricity from space: the future alternative? (cf. [58,59])

Power could be produced in space for terrestrial use by a 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 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 current 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 100 fold: 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.

While solar power satellites are the most natural and investigated ones, most studies indicate that they have poorer prospects for economic viability with current technology than space systems using nuclear reactors. The major needed improvements are in (1) efficiency, (2) weight, and (3) cost.

Much R&D would be needed to overcome these obstacles. Some of the primary subjects are (1) alternate propulsion processes, which requires less energy, produces less undesirable emissions, and have higher specific power, (2) reusable unmanned light space vehicles, (3) robotic plant manufacturing and operation, (4) new static energy conversion systems, which have efficiencies much higher than the 6–10% in current systems, (5) advanced dynamic energy conversion systems, which take better advantage of the near-0 K space heat sink, (6) efficient conversion of the solar photon exergy to electricity, (7) higher-efficiency power transmission, (8) effects of space transportation and power transmission on the atmosphere, (9) launch safety, and (10) space nuclear power safety. It is very noteworthy that many of these objectives are of primary importance even just for terrestrial considerations.

Due to the major obstacle of high cost of space transportation, "breeder" concepts are being proposed and should be carefully studied and developed. In these, a small amount of matter is lifted into space to construct the final, larger facility using resources, such as materials and energy, available in space. The moon is often being considered as a source for materials for the construction of such power plants, as well as a base for them.

Clearly, any development of space power must be subject to equitable international and political agreements. Future generation of power in space for terrestrial use will require massive resources, a long time, and strong and fair international cooperation. A staged approach was proposed [58], to first develop components and smaller-scale systems, which would generate not only technological experience but also wider confidence and acceptance by the people, and then build bigger ones.

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.

6. Some recent energy R&D budgets and trends

6.1. Overview

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. The highlights of the requested 2007 budget, especially in comparison with the 2006 one, are as follows [60].

The total USDOE budget dedicated to energy R&D is expected in 2007 to remain at about the same level as that in 2006, about 2.5 b$, and perhaps about 1 b$ more in basic energy sciences (out of the 4.1 b$ USDOE Office of Science that funds also several other areas that are not directly related to energy), for a total of about 3.5–4 b$. Japan's program is above 2.5 b$ (three quarter of which is for fission and fusion), and that of the EU Sixth Framework Programme (2002–2006), annualized, is about 0.7 b$ (0.16 b$ for "sustainable energy systems", 0.12 b$ for "sustainable surface transport", 0.14 b$ for "global change ecosystems", and 0.26 b$ for the nuclear research in Euratom). It is noteworthy that individual European countries also have their own energy R&D budgets that in total exceed that of the EU.

Out of the USDOE energy R&D budget, nearly half is dedicated to energy efficiency and renewable energy programs, and about one-quarter each to fossil and nuclear energy. The most important changes in the 2007 budget include

- $505 million increase in the DOE's Science programs (nuclear physics including major facilities, materials, nanoscience, hydrogen, advanced computing);
- $250 million to begin investments in the Global Nuclear Energy Partnership (GNEP), to
  - enable an expansion of nuclear power in the US and around the world,
  - promote nuclear non-proliferation goals,
  - help resolve nuclear waste disposal issues + $544.5 million for permanent geologic storage site for nuclear waste at Yucca Mountain, Nevada;
- $322 million for the FutureGen project (co-producing electricity and hydrogen from coal with near-zero emissions);
- Biofuels ($149.7 million) and Solar America ($148.4 million) Initiatives;
- $288.1 million for Hydrogen Fuel Initiative (including fuel cells); and
- $60 million for ITER (fusion).

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.

Table 4 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.

6.2. Individual energy directions

6.2.1. Fossil fuels

The fossil fuels USDOE R&D program is about 600 M$, about two-thirds of it dedicated to the "President's Coal Research Initiative". This includes

- The *Clean Coal Power Initiative* (CCPI) is a cooperative, cost-shared program between the government and industry to rapidly demonstrate emerging technologies in coal-based power generation to help accelerate their commercialization.
- The *FutureGen* project (public/private partnership) will establish the capability and feasibility of co-producing electricity and hydrogen from coal with near-zero atmospheric emissions; including those from carbon (w. carbon sequestration):
  - multiproduct output,
  - electrical efficiencies over 60%, and
  - cost of electricity at no more than a 10% increase over that of comparable plants without carbon sequestration,which use coal, biomass, or petroleum coke.
- The *Fuels and Power systems* program provides important research for FutureGen.

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. It is noteworthy that this target still results in an increase of greenhouse gas emissions of 30% over 1990 levels, well above a US ratified United Nations Framework Convention on Climate Change target of stabilization at 1990 levels in 2010.

"Vision 21" [46] is a very extensive and ambitious program that was developed by the USDOE to produce

Table 4
Promising energy research directions and their current US government funding trend

Direction	Potential	Foreseen improvement	Time scale, years	Government funding
Conservation	☆☆☆	50% use	Ongoing	❍
Transportation	☆☆☆	50% use	3–20	☹
Biomass	☆☆☆+	50% US energy	5–50	☺☺☺
Wind	☆☆☆	2.5 c/kWh, 5 MW unit	1–15	☺
Solar PV	☆☆☆+	Competitive price	5+	☺☺
Solar thermal	☆☆	Competitive price	5+	☹☹☹
Geothermal (deep)	☆☆	Competitiveness	25?	☹☹☹
Hydrogen	☆☆		15	☺☺
Fossil fuel thermal power	☆☆	65–75%, ~0 emissions	10–15	☹☹
Oil and gas	☆+			☹☹☹
Coal	☆+		7	☹
Global warming/CO_2	☆☆	0 CO_2 emissions	10–15	☺☺
Fuel cells	☆☆☆	60%+; price	9	☹
Superconductivity	☆☆☆	Orders of magnitude	30+	☹
Nuclear fission	☆	Safety, wastes, proliferation	9	☺☺
Fusion	☆☆☆?	Feasibility	25+	☺
Micro power	☆☆☆	Market penetration	7+	☺☺
Space power	☆☆☆+?	Competitiveness	50?	❍?

☺: increases, ☹: decreases, ❍: no change.

power from fossil fuels by 2010–2015 with the electricity produced by such plants is planned to be cheaper. Vision 21 is a coordinating mechanism that allows coordination of the (USDOE) activities in the various programs towards its overall goal.

Hydrogen-derived form 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.

6.2.2. Nuclear power

Recognizing the impact of global warming and energy independence concerns, the nuclear power program has an 18% increase in R&D, but at some expense of work on the infrastructure and plant life extension, indicating an interest in developing novel power plants.

6.2.3. Biomass

Biomass is an abundant energy resource that is believed not to release net CO_2 when used as a fuel and reduces dependence on foreign fuel imports, and R&D to make it amenable for practical use should be a high priority. The US government has apparently held this viewpoint, at least in principle, and in a joint effort of the Departments of Agriculture, Commerce, Energy, and Interior, the Environmental Protection Agency, National Science Foundation, Offices of the Federal Environmental Executive, Management and Budget, and Science and Technology Policy, and the Tennessee Valley Authority developed "The biobased materials and bioenergy vision" [61]. These agencies were conducting, fully funding, or partially funding over 500 active R&D projects in the biofuels, biopower, and bioproducts areas. There are also more than 400 organizations, including national laboratories, industry, and academia, which are working in partnerships with the Federal government on these projects. In addition, many biomass-oriented businesses already employ people and sell goods. Over 1400 facilities in the biofuels, bioproducts, and biopower industries employ over 100,000 people and sell goods valued over $50 billion.

Considering the fact that biomass at this time accounts for only about 3% of the US energy consumption, this consortium of Federal agencies proposed a "US Bioinitiative", with very ambitious "visionary" goals: to increase the use of bio-based products and bioenergy in the US, over year 2000 levels, by three fold by the year 2010, 10-fold by 2020, and 20–30 fold by 2050. With these increases, biomass would account by 2010 for 25% of the national energy consumption, and for 50% by 2050, making then the US fully energy independent, and in an internationally dominant position in that field. Although this vision appears to be overly ambitious, an important increase in the budget request for 2007 reflects this interest.

6.2.4. Fuel cells

The DOE has been encouraging fuel cell research, aimed at using hydrogen fuel in transportation, but also large stationary power generation units.

7. Possible paths to the future

The first step in any path to the future is more wise 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. 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. 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 PVs, 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: (1) energy conservation, (2) efficient energy conversion and transmission, considering the entire system life cycle, and (3) global warming mitigation with an emphasis on decarbonization when using fossil fuels, on judicious development of renewable energy use, and on long-term-safe and non-proliferable nuclear power with emphasis on fusion and transmutation of long-life highly radioactive process product elements.

Sustainability is only emerging as a science, and must be developed and applied urgently.

Development of sustainability science, to provide analysis and evaluation tools, 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.

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] US DOE. (United States Department of Energy) 〈http://www.energy.gov/〉 (accessed 2/24/2007).
[2] US DOE. Energy Information Administration 〈http://www.eia.doe.gov/〉 (accessed 2/24/2007).
[3] US DOE. Office of Management, Budget, and Evaluation (MBE), Office of Budget, 〈http://www.mbe.doe.gov/budget/〉 (accessed 2/24/2007).
[4] US DOE. Energy efficiency and renewable energy 〈http://www.eere.energy.gov/office_eere/budget.htmll〉 (accessed 2/24/2007).
[5] US DOE. Office of Fossil Energy. 〈http://www.fossil.energy.gov〉 (accessed 2/24/2007).
[6] National Renewable Energy Laboratory. 〈http://www.nrel.gov/〉 (accessed 2/24/2007).
[7] The European Commission website on Energy Research. 〈http://europa.eu.int/comm/research/energy/index_en.html〉 (accessed 2/24/2007).
[8] International Energy Agency. 〈http://www.iea.org/〉 (accessed 2/24/2007).
[9] British Petroleum. Annual review 2006, 〈http://www.bp.com/productlanding.do?categoryId=4426&contentId=7027648〉 (verified changed URL on 8/10/2007).
[10] Lior N. The state and perspectives of research in the energy field. Invited keynote paper in the third international biennial workshop on advances in energy studies: reconsidering the importance of energy, Porto Venere, Italy, 24–28 September 2002. Sienna, Italy: The University of Sienna. p. 351–64,
[11] International Atomic Energy Agency, United Nations, Department of Economic and Social Affairs, International Energy Agency, Eurostat, European Environment Agency. Energy indicators for sustainable development: guidelines and methodologies. Vienna: IAEA; 2005.
[12] Vera I, Langlois L. Energy indicators for sustainable development. Proceedings of Dubrovnik 2005 conferences on sustainable development of energy, water and environmental systems, June, 2005, Dubrovnik, Croatia. Zagreb, Croatia: The University of Zagreb.
[13] DOE EIA. International energy outlook 2007, Report #DOE/EIA-0484(2007) 〈http://www.eia.doe.gov/oiaf/ieo/pdf/world.pdf〉.
[14] International Atomic Energy Agency. 〈http://www.iaea.org/〉 (accessed 2/24/2007).
[15] Wu Z. Future power generation in China, in Panel on ''Future Power Generation,'' ECOS 2005: 18th international conference on efficiency, cost, optimization, simulation and environmental impact of energy systems, Trondheim, Norway, 2005. Also In: Lior N. Brief summary of the ECOS '05 Panel on Future Power Generation. Energy 2007; 32: 254–55.
[16] International Energy Agency. Energy conservation targets 2005–007. 〈http://www.iea.org/Textbase/nptable/2007/korea_t9.pdf〉 (accessed 8/15/2007).
[17] DOE EIA. Assessment of selected energy efficiency policies report SR/OIAF/2005-03 〈http://www.eia.doe.gov/oiaf/servicerpt/aseep/pdf/sroiaf(2005)03.pdf〉 Energy Information Administration Office of Integrated Analysis and Forecasting US Department of Energy, Washington, DC 20585, USA.
[18] Amin SM, Gellings CW. The North American power delivery system: balancing market restructuring and environmental economics with infrastructure security. Energy 2006;31:967–99.
[19] Sundset T, de Koeijer G. Future power generation in oil and gas industry, in Panel on ''Future Power Generation,'' ECOS 2005: 18th International conference on efficiency, cost, optimization, simulation and environmental impact of energy systems, Trondheim, Norway, 2005. Also in: Lior, N. Brief summary of the ECOS '05 Panel on Future Power Generation. Energy 2007; 32:255–56.
[20] US DOE. How much nuclear waste is in the United States? 〈http://www.ocrwm.doe.gov/ym_repository/about_project/waste_explained/howmuch.shtml〉 (accessed 8/15/2007).
[21] US DOE. Annual amounts of waste and SNF generation (Sum 2). 〈http://cid.em.doe.gov/Modules/Reporting/Summary/SUM2.pdf〉.
[22] US DOE. Department of Energy Five Year Plan FY 2007–FY 2011, vol. II 〈http://www.em.doe.gov/PDFs/170016EM_FYP_Final_3-6-06.pdf〉 (accessed 8/15/2007).
[23] Saleska S. Nuclear legacy, September 1989. Public Citizen report, 215 Pennsylvania Ave., S.E. Washington, DC, USA.
[24] United States Nuclear Regulatory Commission. Fact Sheet: Plutonium, October 2003. USNRC Office of Public Affairs, Washington, DC 20555, USA.
[25] Kessler G. Requirements for nuclear energy in the 21st century—nuclear energy as a sustainable energy source. Prog Nucl Energy 2002;40:309–25.
[26] US DOE. Gen IV Nuclear Energy Systems 〈http://www.ne.doe.gov/genIV/neGenIV1.html〉 (accessed 8/19/2007).
[27] Lake JA. The fourth generation of nuclear power. Prog Nucl Energy 2002;40(3–):301–7.
[28] Salvatores M. Transmutation: issues, innovative options and perspectives. Prog Nucl Energy 2002;40:375–402.
[29] Artisyuk V, Saito M, Stankovsky A. Challenge of transmutation of long-lived nuclides. Prog Nucl Energy 2005;47:327–38.
[30] Rubbia C. Today the world of tomorrow—the energy challenge. Energy Convers Manage 2006;47:2695–7.
[31] Bianchi F, Artioli C, Burn KW, Gherardi G, Monti S, Mansani L, et al. Status and trend of core design activities for heavy metal cooled accelerator driven system. Energy Convers Manage 2006;47:2698–709.
[32] Mathieu P. Future of nuclear power generation, in Panel on ''Future Power Generation,'' ECOS 2005: 18th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems, Trondheim, Norway, 2005. Also In: Lior, N. Brief summary of the ECOS '05 Panel on Future Power Generation. Energy 2007;32:258–9.
[33] United Nations. World Energy Assessment. New York: UNDP; 2000.
[34] Lepore JA, Shore S, Lior N. Retrofit of urban housing for solar energy conversion. Hous Sci 1978;2(6):483–98.
[35] Lior N. Retrofit for solar heating and cooling. In: Boer KW, editor. Advances in solar energy, vol. 5. New York: Plenum Press; 1989. p. 360–401 [Chapter 5].
[36] Lior N. Solar energy and the steam Rankine cycle for driving and assisting heat pumps in heating and cooling modes. Energy Convers 1977;16(3):111–23.
[37] Lysen E. Renewable energy: the transition phase, in Panel on new energy sources, better energy converters and viable energy technologies, the third international biennial workshop on advances in energy studies: reconsidering the importance of energy, Porto Venere, Italy, 24–28 September 2002. p. 351–64.
[38] US DOE. Solar Energy Technologies Program, Solar America Initiative: a plan for the integrated research, development, and market transformation of solar energy technologies, DRAFT February 5, 2007 SETP-2006-0010 〈http://www1.eere.energy.gov/solar/solar_america/pdfs/sai_draft_plan_feb5_07.pdf〉 (accessed 8/19/2007).
[39] Cornelius C. DOE Solar Energy Program overview market trends, strategy, R&D pipeline, next steps. 〈http://www1.eere.energy.gov/solar/solar_america/pdfs/solar_energy_comp_overview_0807.pdf〉 DOE Solar Energy Technologies Program, August 2007 (accessed 8/19/2007).
[40] US DOE. New world record achieved in solar cell technology, 〈http://www.energy.gov/news/4503.htm〉 December 5, 2006 (accessed 8/19/2007).
[41] EWEA (The European Wind Energy Association). Powering the future: EWEA 2006 annual report 〈http://www.ewea.org/fileadmin/ewea_documents/documents/publications/reports/ewea-report2006.pdf〉, Brussels, Belgium (accessed 8/19/2007).
[42] Jensen PH. Future Wind Power Generation, in Panel on ''Future Power Generation,'' ECOS 2005: 18th international conference on

efficiency, cost, optimization, simulation and environmental impact of energy systems, Trondheim, Norway, 2005. Also In: Lior, N. Brief summary of the ECOS '05 Panel on Future Power Generation. Energy 2007;32:259.
[43] GWEC (Global Wind Energy Council). Wind Force 12. 〈http://www.ewea.org/fileadmin/ewea_documents/documents/publications/reports/wf12-2005.pdf〉 (accessed 2/24/2007), Brussels, Belgium (accessed 8/19/2007).
[44] Keppler F, Hamilton JG, Brass M, Rockmann T. Methane emissions from terrestrial plants under aerobic conditions. Nature 2006; 439:187–91.
[45] Kavangh E, editor. Looking at biofuels and bioenergy. Science 2006;312:1743–8.
[46] US DOE. Office of Fossil Energy Vision 21 program 〈http://www.fossil.energy.gov/coal_power/vision21/〉 (moved to 〈http://www.fossil.energy.gov/programs/powersystems/vision21/index.html〉, access verified 8/10/2007).
[47] Majumdar A, Tien CL. Micro power devices. Microscale Thermophys Eng 1998;2:67–9.
[48] Peterson RB. Size limits for regenerative heat engines. Microscale Thermophys Eng 1998.
[49] Ohadi MM, Buckley SG. High temperature heat exchangers and microscale combustion systems: applications to thermal system miniaturization. Exp Therm Fluid Sci 2001;25(5):207–17.
[50] Lee DH, Park DE, Yoon JB, Kwon S, Yoon E. Fabrication and test of a MEMS combustor and reciprocating device. J Micromech Microeng 2002;12(1):26–34.
[51] Holladay JD, Jones EO, Phelps M, Hu J. Microfuel processor for use in a miniature power supply. J Power Sources 2002;108(1–2): 21–7.
[52] Kribus A. Thermal integral micro-generation systems for solar and conventional use. ASME J Sol Energy Eng 2002;124:180–97.
[53] Holladay JD, Jones EO, Phelps M, Hu J. High-efficiency microscale power using a fuel processor and fuel cell. Proc SPIE Int Soc Opt Eng 2002;4559:148–56.
[54] McDonald CF, Rodgers C. The ubiquitous personal turbine-a power vision for the 21st century. ASME J Eng Gas Turbines Power 2002;124:835–44.
[55] Campanari S. Full load and part-load performance prediction for integrated SOFC and microturbine systems. ASME J Gas Turbines Power 2002;122:239–46.
[56] Massardo AF, McDonald CF, Koriakinitis T. Microturbine/fuel-cell coupling for high efficiency electrical power generation. ASME J Gas Turbines Power 2002;124:110–6.
[57] Magistri L, Costamagna P, Massardo AF, Rodgers C, McDonald CF. A hybrid system based on a personal turbine (5 kW) and a solid oxide fuel cell stack: a flexible and high efficiency energy concept for the distributed power market. ASME J Gas Turbines Power 2002; 124:850–7.
[58] Glaser PE, Davidson FP, Csigi KI, editors. Solar power satellites, the emerging energy option. New York: Ellis Horwood; 1993.
[59] Lior N. Power from space. Energy Convers Manage J 2001; 42:1769–805.
[60] US DOE. FY 2007 DOE budget request to Congress, 〈http://www.mbe.doe.gov/budget/07budget/Start.htm〉.
[61] US DOE. The biobased materials and bioenergy vision. Draft, 18 July 2001. Originally at DOE URL 〈http://www.bioproducts-bioenergy.gov/pdfs/BIOENGY_BRCH_0718.pdf〉. Now at 〈http://sungrant.tennessee.edu/NR/rdonlyres/0EC8C392-FC7D-4761-990-B-10A5470CB8BD/0/vision.pdf〉 (access verified on 8/10/2007).