THE STATE AND PERSPECTIVES OF RESEARCH IN THE ENERGY FIELD

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ABSTRACT

Energy research has presently *relatively* high priority, particularly *at this moment* because of the global warming consequences. It is funded/conducted at a lower level of intensity than it was in the decade following 1973, when it was motivated from the grass roots due to quasi-scientific predictions of imminent depletion of fluid fuels resources by the very beginning of the 21^{st} century, anxiety of dependence on hostile, and unreliable oil suppliers. The sense of urgency in energy research is lower 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. A most worrisome consequence is the decimation of research programs in alternative energy resources, from solar to nuclear, especially in the U.S. Current R&D efforts and budgets in the main energy resources and technologies, and promising areas outside of the mainstream, such as micropower and power from space, are reviewed and assessed.

1. INTRODUCTION

This paper is a brief summary about the current state and perspectives of energy research. It is based primarily on the situation in the U.S., which has the largest funding and activity in the field, and to lesser depth, on the situation in the European Union (EU). The actual numbers are taken from the excellent web sites of the U.S. 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], and the International Energy Agency [8]. The analysis, interpretation, and comments are entirely the author's and do not represent any institutional or government views.

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 21-century, and by anxiety of dependence on hostile and unreliable oil suppliers. The sense of urgency in energy research diminished from the late 1980-s because of successful energy conservation improvements, relatively low fluid fossil fuel prices, reasonable reliability of the fossil fuel supply, 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 70-s and 80-s did not meet the somewhat unrealistic expectations, such as independence from oil by the mid 1980-s 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 U.S.

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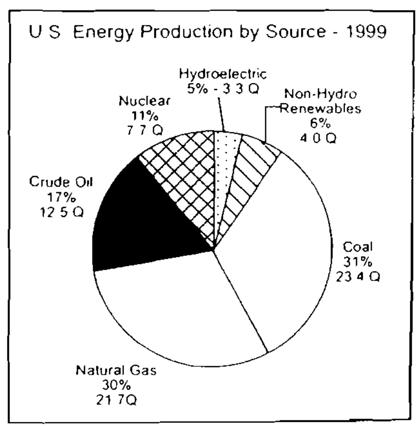
This decline has been somewhat arrested in the past few years, primarily because of the broad acceptance that global warming is a fact, caused primarily by increasing emissions of CO_2 due to energy related combustion. This has invigorated R&D in efficiency improvement, use of energy sources that do not produce CO_2, and in methods for CO_2 separation and sequestration. While not nearly at the earlier levels, interest in the energy issue and support for energy R&D are on the rise, abetted by the frequent political unrest in the oil producing regions.

The USDOE. total energy research, development, and science budget for 2002 is about 5.8 b$ (2.5 b$ for the Energy and Environment program, and 3.3 b$ for the Science program), slightly rising relative to the past couple of years. 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.

2. ENERGY CONSUMPTION, R&D OBJECTIVES AND ACCOMPLISHMENTS IN THE U.S.

The U.S. consumes, regrettably, the largest amount of energy per capita in the world (370 GJ/person year), and the energy sources are shown in Fig. 1 Noteworthy are the facts that natural gas has replaced some of the use of oil, and that coal is the largest energy source, similar in quantity to that of natural gas. Oil has declined to 17% of the consumption, and nuclear power and the use of renewables (besides hydro) remain approximately stable at 11% and 6%, respectively.



In 1999, the United States consumed over 97 quadrillion British thermal units (quads) of energy, of which 84% came from coal, petroleum and natural gas resources The majority of the coal is consumed in the electric utility sector to generate electricity for use in the buildings and industrial sectors. The majority of the petroleum is consumed in the transportation sector. In addition, relatively equal portions of natural gas are consumed in the buildings and industrial sectors, with a smaller portion consumed by electric utilities to generate electricity that is sold to the end-use sectors If domestic energy production only grows at the rate experienced over the last ten years, the May 2001 National Energy Policy (NEP) Report projects the following consumption increases during the next twenty years: oil +33%, natural gas +50% and electicity, of which coal is the dominant resource, +45%. At that point in time, the estimated energy consumption-production gap could be nearly 60 quads, or almost a 50% shortfall. To head off such a grim scenario, the Department's Energy Efficiency Program is structured to address specific needs of four major user sectors: Buildings, Federal Energy Management, Industry and Transportation, as well as a new power delivery system known as Distributed Energy Resources

Figure 1 U.S. energy production by source – 1999 [2] 1 quadrillion Btu ("Quad") = 10^{15} Btu = (1.055) 10^{18}J = 1.055 EJ

At the same time, significant progress is seen in energy efficiency, where the energy use efficiency has increased by 50% from 1967 o 2001 (from 40% to 60%, Fig. 2), and the energy consumption per dollar of real GDP has dropped by 42% between 1973 and 2000 (Fig. 3).

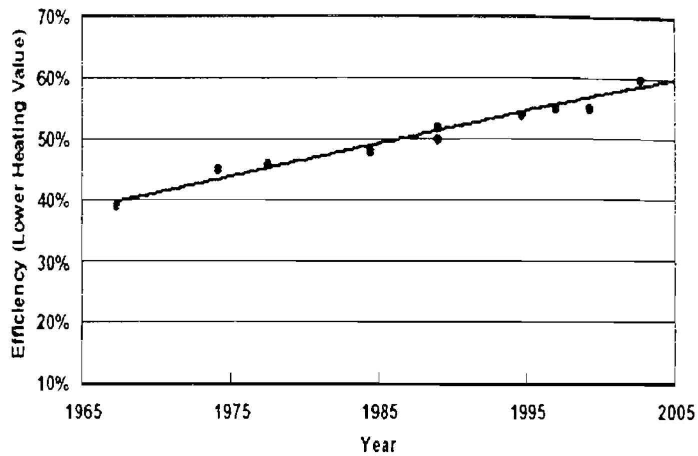


Figure 2 Energy efficiency in the U.S. [2]

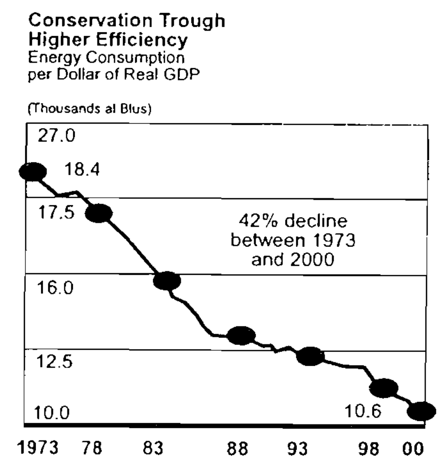


Figure 3 Energy consumption per dollar of real GDP [1]

In automotive transportation the average fleet of passenger cars and light trucks has increased its efficiency from 14.5 mpg (6.2 km/liter) in 1975, to a peak of 25.9 mpg (11 km/l)in 1987 (declined slightly to 24.6 mpg (10.5 km/l) in 1997), Fig. 4. Even more significantly, this improvement was accomplished alongside with a 63% increase in the average fleet horsepower (Fig. 5). These remarkable improvements are a result of the effort invested toward this goal, but also because it was relatively easy to improve a situation that was rather bad to begin with.
Coal is the most abundant U.S. energy resource, with domestic reserves exceeding the energy potential of the world's oil reserves. About 90% of all coal produced in the U.S. is used for electricity generation, and over half of the U.S. electricity is produced by coal-fired power plants. The DOE foresees the use of coal for the foreseeable future, and realizes that it must therefore develop and demonstrate technologies that will enable the continued use of coal in an environmentally sound manner.
Currently, the United States imports approximately 55% of is consumption of petroleum crude and finished products, projected to increase by 2020 to 67%. It looks at coal-derived hydrogen as an important part of a strategy to diversify and expand its domestic fuel resource base, reduce emissions from the transportation sector, and help limit reliance on imported oil. Of human-made emissions, the U.S. transportation sector is responsible for nearly 80 percent of the carbon monoxide (CO), over one half of the nitrogen oxides (NOx), and 40 percent of the volatile organic compounds (VOC), and 35% of the U.S. energy sector's carbon dioxide production.

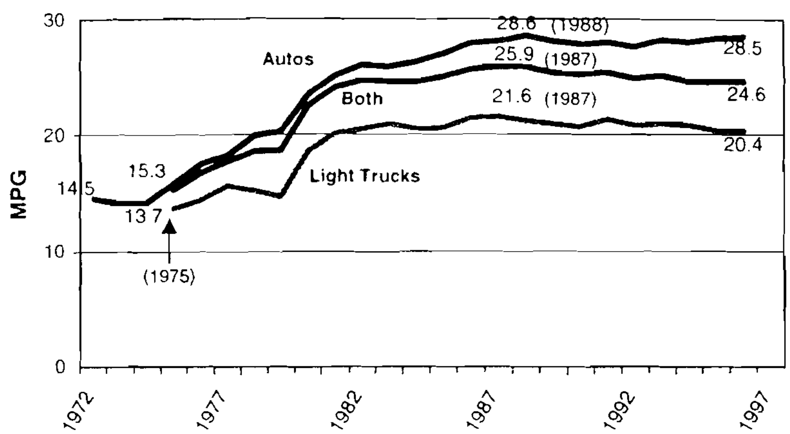


Figure 4 Energy efficiency history of automotive transportation in the U.S. [2] 1 MPG (miles per gallon) = 0.425 km/litre.

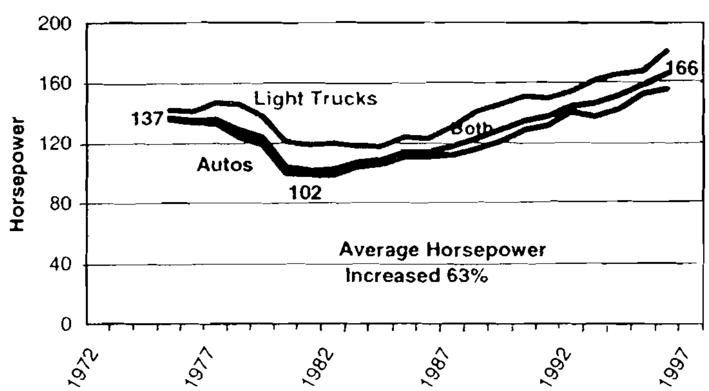


Figure 5 Horsepower history of automotive transportation in the U.S. [2]

The current U.S. administration declared that "President Bush's policy framework secures energy, sustains development, protects environment" (Robert Card, Undersecretary, U.S. Department of Energy, August 30, 2002 [9], and has stated its national energy action plan to "Develop Long Term Options for Secure Sustainable Energy", by the following activities:

- Hydrogen
  - Regard it as a clean transportation fuel of the future
  - To be produced from coal, emissions-free nuclear, renewables, or emissions trapped fossil fuels
- Fusion
  - The US is one of the world's largest supporters of fusion research
  - Considering joining the ITER (fusion, Tokamak) consortium

- Emissions-trapped fossil
  - Work with IEA
- Development of generation IV nuclear power plants

It aims to "Fulfill the President's Commitment to Reduce Greenhouse Gas Emissions" [10] by

- "Integrating environment and energy
- Increased research commitments to carbon sequestration and emissions reduction enabling the clean use of fossil energy
- Increased nuclear -- our largest source of emissions-free energy
- Increased renewables and energy efficiency -- resources of increasing importance".

While the government budget indeed supports all these objectives, the actual funds allocated to the expressed environmental concerns and renewable energy development appear to be insufficient, and in some cases declining as shown in more detail below. It is noteworthy however, despite the administration refusal to sign the Kyoto 1997 protocol, that it is its stated goal to reduce greenhouse gas intensity by 18% by 2012.

3. 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. The total USDOE budget dedicated to energy R&D (including weatherization and excluding the maintenance of the petroleum and oil shale reserves) is expected in 2003 to remain at about the same level as that in 2002, about 2.5 b$, and perhaps about 1 b$ more in basic energy sciences (out of the 3.3 b$ USDOE Office of Science that funds also several other areas which are not directly related to energy), for a total of about 3.5b$. Out of this, nearly half is dedicated to energy efficiency and renewable energy programs, about one-quarter to fossil energy, and somewhat less to nuclear energy, including 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 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. As can be seen, some promising areas such as global warming prevention (increase by 68%, to 54 M$), superconductivity (by 48% to 48 M$), wind, hydrogen, and micro-power systems have indeed increased in funding, but some other highly promising areas, such as solar photovoltaics, transportation, biomass, and fuel cells, had a reduction.

4. FOSSIL FUELS

As stated by the USDOE, "the mission of the Fuels program is to create public benefits by conducting the research necessary to promote the transition to a hydrogen economy. Research will target reducing costs and increasing efficiency of derived hydrogen from coal feedstocks as part of the Freedom Fuel Initiative."

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

A very extensive and ambitious program, "Vision 21" [11] was developed by the USDOE to produce power from fossil fuels by 2010-2015 with-near- zero pollutants (<0.1 New Source

Table 1. Promising energy research directions and their current U.S. government funding trend.

Direction	Potential	Foreseen Improvement	Time scale, yrs	Govm't funding
Conservation	**	50% use	Ongoing	O
Transportation	***	50% use	3-20	☹
Biomass	***+	50% US energy	10-50	☹
Wind	***	2.5c/kWh, 5MW unit	1-15	☺☺
Solar PV	***+	competitive price	5+	☹
Solar thermal	**	competitive price	5+	☹☹☹
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%+ eff.; price	9	☹
Superconductivity	***	orders of magnitude	30+	☺☺☺
Nuclear fission	*	safety, wastes, proliferation	9	☹
Fusion	***?	feasibility	25+	O
Micro power	***	Market penetration	7+	☺☺
Space power	***+?	competitiveness	50?	O?

Performance Standards) at lower cost, options for no net CO_2 emissions, higher efficiency: >60% with coal as fuel and•>75% with natural gas, fuel flexibility (coal, natural gas, wastes), constructed as a flexible set of integrated modules that could also produce high-value commodities. Remarkably, the electricity produced by such plants is planned to be cheaper. Vision 21 is a coordinating mechanism that allows us to coordinate the activities in the various programs towards its overall goal. Funding for Vision 21 is made available through the line item programs, e.g., integrated gasification combined cycle, turbines, advanced research, etc. The total budget for activities that support Vision 21 was about $67 million in FY02 and is about $78 million in FY03.

The oil and gas R&D budget has been reduced by 40%, to 58M$, and the "Clean Coal Technology" program by 6%, to 40 M$ (but with some deferred moneys transferred to the fossil energy R&D budget).

"President's Coal Research Initiative" is, for 2002, 333 M$, including the "Clean Coal Power

Initiative" (146 M$, matching funds for industry to do RD&D of advanced technologies in coal-fired power plants), Central Systems (94 M$: innovations for existing plants 23 M$, integrated gasification combined cycle 42 M$, pressurized fluidized bed 11 M$, turbines 18 M$), Sequestration R&D (31 M$), Fuels from coal (34 M$, to be nearly zeroed next year), and Advanced Research (28 M$). Distributed generation systems, primarily fuel cells and innovative systems concepts is about 57 M$, with significant reductions projected for future years.

The stated midterm performance goal of the Clean Coal Power Initiative is to develop advanced coal-based power generation technologies that improve efficiency from 2002 baseline of 40% to 50% by 2010, with environmental and economic performance capable of achieving 90% mercury removal at a cost of 70% of current technology by 2010, 0.15 lb/MMBtu NOx at 75% of the cost of current technology (Selective Catalytic Reactors), and lower capital costs for gasification technologies from $1200 per kilowatt of capacity, and co-produce heat, fuels, chemicals or other useful byproducts.

It appears that most of the research and development funds are dedicated to the construction and testing of large facilities, at the detriment of basic research intended to address high-risk high-potential approaches, such as, just as an example, the reduction of basic thermodynamic irreversibilities inherent to combustion and other chemical reactions [11,12].

5. NUCLEAR POWER

While the requested USDOE R&D budget seems to be large, 251 M$ (reduced by 15% this year), much of that money is for the maintenance of existing experimental facilities, a smaller portion for R&D intended to prolong the life and abet the safety of the aging U.S. nuclear power plant inventory, and very little is intended for new directions, such as the "Generation IV" inherently safe reactors.

It appears that the research has a very gradual and timid approach. While the focus on safety, waste treatment, and more recently emphatically on prevention of proliferation, addresses the major problems, it seems to do so using conventional, low-risk approaches. One example is the need to address efficiency innovatively: nuclear power plants operate at a thermal efficiency of only about 29% to 35%, and Second Law analysis shows that over 80% of the exergy destroyed during plant operation is a result of the highly-irreversible fission and heat transport processes within the reactor vessel [14]. New ideas such as the "Nuclear Generator", to find ways to generate power from the high-kinetic-energy fission (or fusion) products before this energy was converted to heat [14,15] aren't explored.

6. HYDROGEN

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 $30/barrel crude oil equivalent when integrated with advanced coal power systems, but the budgets allocated for that purpose do not support this priority adequately. The USDOE hydrogen fuel R$D budget is up 37% to 40M$. The stated major accomplishments in 2001 are that a unit produced 20 m^3/h hydrogen by steam reforming of biomass pyrolysis oil. The target for 2002 is to construct a process development unit of a ceramic membrane system for hydrogen production, and for 2003 to complete the design, development and testing of the 10,000 psi (~69 MPa) hydrogen storage tank

Despite its desirability and the declared plans for its development, widespread use of hydrogen as fuel in the foreseeable future appears, for various reasons, to be doubtful, because of the high energy demand for its production, and issues of safety, storage, and distribution.

7. SOLAR ENERGY

The USDOE solar energy research budget is approximately stable at 88 M$. The small amount available for concentrating solar power was eliminated, leaving most of the budget for photovoltaics (PV). A major PV accomplishment in 2001 is stated to be the development of a 14% efficient prototype thin film PV module. The stated target for 2002 is to reduce manufacturing costs of a PV module to $2.25/We (equivalent to electricity price of 0.20-0.30 $/kWh from such a solar power plant), and for 2003 further to $2.10/We (0.18-0.28/kWh).

8. WIND ENERGY

The last decade has seen very significant improvements in wind energy technology, which in the 1980-s was miniscule and has now reached competitive pricing and an exponentially increasing market penetration with sales of 5 b$/year, and 29% growth/year that makes it the fastest growing electric power production technology. In the year 2000 it reached a capacity of more than 18,000 MW and is projected to reach by the year 2005 more than 50,000 MW (Fig. 6). It is noteworthy that wind power generators in the 1980-s were about 10 m in diameter and generating 50 kW, growing by 2000 to about 60 m, 750 kW, and projected by 2010 to grow further to 100 m, 5MW.

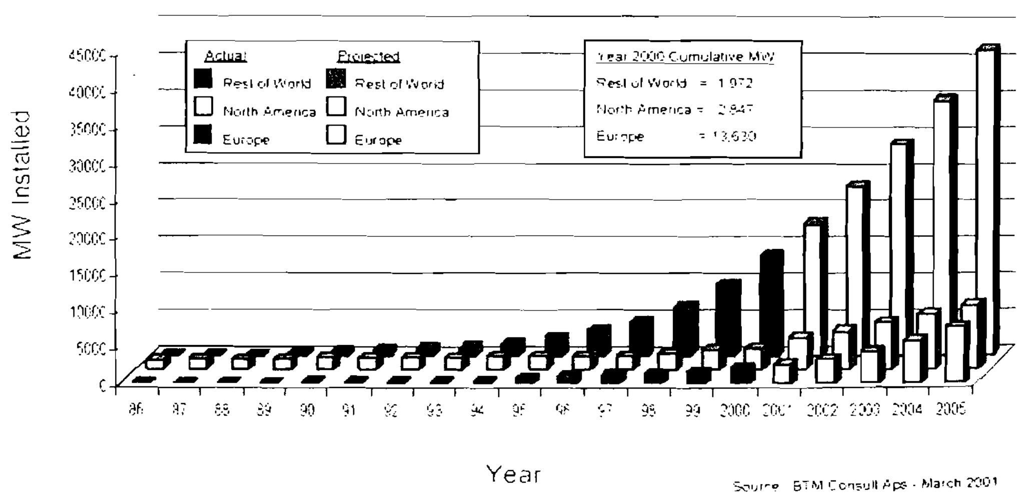


Figure 6 Growth of wind energy worldwide [6].

Europe is by far the leader in wind power generation, with Danish companies accounting for about 45% of the world market, but the US plans to provide at least 5% of the nation's electricity with wind by 2020, and as soon as 2005 establish the U.S. wind industry as an

international technology leader capturing 25% of world markets.
The main technical accomplishments of the USDOE wind energy program are stated as availability increased to 98%-99%, certification of the equipment to international standards, and the development of tools to help industry build better wind turbines. These tools include computer models, advanced controls to adjust turbine operation to maximize energy production and minimize wear, development of adaptive blades that could increase turbine performance bas much as 35%, wind forecasting to allow utilities to predict wind generation for the next day, and optimal methods for wind integration to help utilities understand the effects of wind generation on conventional generation, transmission, distribution, and other services.
The primary technical goals of the program are to develop by 2002 advanced wind turbine technologies capable of reducing the cost of energy from wind to 2.5 cents/kWh (in 15 miles/h (24 km/h) winds). While the wind energy R&D budget was increased last year by 14%, to 44 M$, it is hard to imagine that the ambitious goals will be met by such a small budget.

9. BIOMASS ENERGY

Biomass is an abundant energy resource that essentially does not release net CO_2 when used as a fuel, 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" [16]. These agencies are conducting, fully funding, or partially funding over 500 active research and development 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 1,400 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 U.S. energy consumption, this consortium of federal agencies proposed a "U.S. Bioinitiative", with very ambitious "visionary" goals: to increase the use of biobased products and bioenergy in the U.S., over year 2000 levels, by 3-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 U.S. fully energy independent, and in an internationally dominant position in that field.
The proposed biomass research needed for this major progress includes development of (1) "new" biomass, via improved land use, waste utilization, and crop management, together with modified processing methods; new methods of cultivating and harvesting aquatic organisms; genomics and transgenic plants (e.g. to engineer plants and microorganisms that would yield novel polymers, or to maximize carbon for high-energy content), and 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, and (2) traditional biomass (lignin and cellulosics) by more efficient gasification, enzymatic conversion of lignocellulosic biomass to ethanol, and cultivation of hybrid rapidly growing plants (e.g., poplar or willow,

switchgrass).

Reduced by 2% to 86 M$, the current U.S. D.O.E. biomass energy program has undertaken, however, much more modest goals. Its stated mission is to develop approaches for expanding the use of biomass for energy and industrial products by making biorefinery technologies cleaner and more efficient, reliable, and lower in cost, by focusing on investigating the feasibility of gasification for producing biomass-derived fuels such as gasoline, diesel, and hydrogen, development of processes for producing cellulosic ethanol, and biobased product R&D to produce value-added chemicals, engine oils, solvents, plastics and improved enzymes.

10. FUEL CELLS

Fuel cells are devices that produced electricity directly from fuel and oxygen (air) with nearly no moving parts and fewer components than conventional power plants. At least in principle, they can operate at relatively high efficiencies even at temperatures much lower than those used in conventional power plants. A number of types exist, the main being:

- Proton Exchange Membrane (PEM) fuel cells: operating at relatively low temperatures, high power density, and efficiencies of 40-50%. They vary their output quickly to meet shifts in power demand and are thus suitable for automotive applications. However, they need pure hydrogen to operate and very susceptible to "poisoning". Work is under way to produce more tolerant catalyst systems along with membranes capable of operating at higher temperatures.
- Alkaline fuel cells: operate at around 80°C and therefore start quickly. They produce low power density, and are too bulky for automotive use. They are relatively cheaper to manufacture and could be used in small stationary power generation units. They are extremely sensitive to carbon monoxide and other impurities.
- Phosphoric acid fuel cells: are the most commercially advanced. Liquid phosphoric acid is the electrolyte, which has low volatility, they operate around 150 to 200° C, and have higher tolerance to impurities. They are ~40% efficient, simply constructed, and stable. Currently working units with outputs from 0.2-20MW provide power worldwide.
- Molten Carbonate Fuel Cells (MCFC): use molten lithium potassium or lithium sodium carbonate salts as the electrolyte, operating at 650°C. The fuels are hydrocarbons, which are reformed internally to generate hydrogen. Efficiency is up to 60%, or 80% if waste heat is used. No problems are experienced with carbon monoxide poisoning at these high temperatures. It takes a relatively long time to reach operating temperature, and they are thus unsuitable for automotive use but are attractive for use in large-scale industrial processes and for power production.
- Solid Oxide Fuel Cells (SOFC): operate at 800-1000° C and reach efficiencies of 60% and even higher in hybrid configurations with turbines. They are resistant to carbon monoxide poisoning and can use fossil fuels directly. They are likely to be used for industrial generation of electricity combined with heat.
- Direct Methanol Fuel Cells (DMFC): are variants of PEM fuel cell. They operate at ~120° C with efficiencies of around 40%. They are aimed currently at battery replacement, e.g. for powering mobile phones and laptop computers.
- Regenerative fuel cells would produce their own fuel, such as by incorporating electrolysis, the reverse fuel cell reaction, to produce hydrogen in a closed system.

As shown above, various important technical issues must be resolved before fuel cells attain significant market penetration, but vigorous R&D is highly recommended. It is somewhat surprising that the USDOE budget was reduced last year by about 19%, to 49 M$. The current USDOE strategy in the near-term (2004-2006) is to develop and conduct initial proof-of-concept tests of low-cost 3-10 kilowatt solid-state fuel cell modules for distributed and auxiliary power unit applications; in mid-term (2010) develop and test fuel cell prototype modules capable of manufacture of $400 per kilowatt (a ten-fold reduction from today's cost), and develop combined cycle $400 per kilowatt gas-based fuel cell/turbine hybrids under Vision 21 Hybrids that will enable the design of coal-fueled hybrid power plants.

11. MICRO POWER SYSTEMS (cf. [17-21])

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 [22]. Since the power produced by such a device is of the order of milliWatts at best, it doesn't at first glance appear that they will be used to produce a significant fraction of the overall power demand. At the same time one can't help but recall 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 where continuum theory often can't be used. The shortness of the heat flow paths in thermally driven devices, whether solid state or using conventional power cycle using a working fluid, causes a significant fraction of the heat transported from the heat source to the sink to bypass, through the device structure, the power generation part of the device. This reduces the power generation efficiency as the device becomes smaller.

If combustion is incorporated into the device, such as in micro gas turbine systems, the relatively large surface to volume ratio may cause inordinate heat losses, making the reaction difficult to sustain., and the microcombustor walls may have other undesirable effects on the process. When fluid flow is included in the device, feed and exhaust connections are hard to incorporate without causing an inordinate increase in the size of the device, and the flow would experience relatively large pressure drops.

All that said, the extraordinary benefits of micropower generators in many known and yet unknown applications make the challenges associated with their development very worthwhile.

"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, are being introduced to the market for distributed generation, for homes and commercial applications [23]. Studies of combining such microturbines with solid oxide fuel cells indicate the possibility of reaching efficiencies of 60% [24-26]

12. ELECTRICITY FROM SPACE: THE FUTURE ALTERNATIVE? (cf. [27,28])

Power can 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.

On the one hand, 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 inevitable: (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.

On the other hand, 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.

Compared with nuclear space power, most studies have concluded that solar power satellites appear to have poorer prospects for economic viability with current technology. 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, (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.

Superpower animosities have been the major political obstacle in all areas of commercial development in space. Although they have now abated, the use of space for power production still faces important political problems. One is that at most a handful of countries are capable of developing and implementing this technology at this time. The other countries, which would in fact be the most needy power customers, must be reassured that this power supply wouldn't be governed by monopolistic economics, and wouldn't subject them to undue political pressure by the vendors. An increasingly peaceful world and healthy free market economics governed by international law are the obvious remedies for solutions equitable to all participants. Both, but especially the former, are difficult to establish.

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 [27], which, instead of engaging all at once in the development and construction of a large scale space power generation station. would gradually develop components and smaller scale systems, which would generate not only technological experience but also wider confidence and acceptance by the people. This staged approach would be strongly fortified if applications collateral with space power, such as space-to-space power beaming for powering satellites, power relaying by orbital microwave or laser beam reflectors, and orbital mirrors for extended periods of terrestrial illumination, are developed. 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.

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