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Keynote paper

Thoughts about future power generation systems and the role of exergy analysis in their development

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Abstract

In face of the likely doubling of the world population and perhaps tripling of the power demand over the next 50 years, this paper (1) presents some thoughts on the possible ways to meet the power demands under the constraints of increased population and land use while holding the environmental impact to a tolerable one, and (2) outlines the ways exergy analysis may be effectively used in the conception and development of such processes. To effectively develop the innovative power generation systems needed in the 21st century, irreversibility and exergy analysis should be much more focused on the intrinsic process details.

Keywords: Power generation; Second law analysis; Exergy analysis; Nuclear power; Space power

1. Introduction

The expected large rise in power demand during the coming 21st century is accompanied by mounting problems with power plant siting, environmental impact, resource shortages, and increasing shortage of available space for fuel and power generation and distribution. Although industry, often assisted by government, is making gradual progress in addressing these problems, the pace of the progress, when extrapolated into the future, is not likely to meet humanity's needs. Even worse, if not accelerated, it may lead to irreversible harm to the environment and to the ability of future generations to continue their progress towards improved living conditions.

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The omniferous politician, publisher, and scientist Benjamin Franklin (who, I may add, has also founded the University of Pennsylvania in 1740), a believer in conservation and frugality, has written "a penny saved is a penny earned". In the energy area in general, and in power generation in particular, one could safely say that "a Joule saved is worth significantly more than a Joule earned": it takes significantly more than 1 J of energy to generate 1 J of power. This is amplified severalfold when one considers the resources and environmental impact associated with the construction and operation of a power plant. It is clear therefore that the first priority in meeting the challenges of the coming century is energy conservation, but not implemented in a way that would deprive large fractions of humanity of basic comforts of life. Indeed, as one of the drafters and signers of the US constitution, Franklin has believed in facilitating people's "pursuit of happiness" and practiced it himself whenever he could. Such pursuit is made very difficult, or impossible, for a population living under draconic energy conservation measures.

Further, improved power generation efficiency and reduced emissions, species and energy, are obvious paths that are being taken continuously and should be accelerated further. This may be achieved by gradual improvement of existing processes, and the invention and development of new ones.

Finally, humanity may need to look up to space for its future energy needs.

Human knowledge and intelligence, accompanied by expertise in many disciplines led by science, engineering, economics, and sociology, must be aggressively employed to solve the foreseen problems. This must be assisted strongly and guided by governments, industries and institutions that have a longer-term commitment to this vital endeavor than the next elections or shareholders' meeting.

2. Power demand

Assuming a moderate 1.4% population increase, driven primarily by developing countries which have a gradually improving standard of living, the current earth population of about 5×10^9 is going to double to 10^{10} within 50 years, and the associated energy demand is expected to have a 1.5–3 fold increase [1]. With increased introduction of modern technology into the world households, and especially with the likelihood of gradual conversion to electric vehicles, electric power would increasingly dominate the demand.

3. Energy and power sources

Barring political upheavals and environmental disasters, most prognosticators indicate that the conventional raw energy sources, such as fossil and nuclear fuels, are sufficient at least into the middle, and probably through, the 21st century [1]. Their actual use for producing electric and transportation power is, however, more problematic due to increasing environmental impact, public concern, regulatory complexity, community resistance to plant siting, and financial sector apprehensiveness (at least during the transition period) about the rapidly expanding deregulatory process for the utilities and about its consequences.

Fossil fuels will clearly be effectively depleted sooner or later, with a distinct possibility that this would happen in the coming century if their consumption continues at the current pace. Three energy sources with longer-term potential are nuclear fission breeder reactors, fusion reactors, and solar energy, with the latter being by far the longest lasting and most benevolent. Regrettably, much research and development is still needed to make either of these sources usable practically for satisfying the major energy demands foreseen. The breeder is considered to be unsafe in many ways, fusion research is still far from delivering an economical working plant, and the diffuse nature of solar energy makes it more expensive than currently used power generation technologies.

4. Environmental impact

Until a decade ago the primary concern about energy impacts on the environment was of a local nature, focused on the negative consequences of mining the fuels and of producing power. Increasing flow rates of long-distance transportation of fuels with the associated oil spills, the Chernobyl disaster, and the near-disaster of Three Mile Island have identified that energy-related environmental impact has regional, multi-national, and perhaps global consequences which must be addressed rapidly. Global warming due to CO_2 and other emissions is now widely considered to be a real phenomenon, and has already resulted in the international ban on CFCs, and evolving agreements to control and limit CO_2 emissions. The latter would have a very significant impact on the ways we would convert fuels and produce power, and is a powerful motivator for scientific and engineering progress in these areas.

5. Thermo-mechanical power generation systems

Regardless of the heat source (fossil fuel, nuclear, solar, fusion, geothermal, ...), it is highly likely that thermo-mechanical systems, such as increasingly advanced versions of Rankine, Brayton, Stirling, Diesel, and Otto cycles, will dominate power generation technology well into the next century. As demonstrated in [2], the advances sought would fall into a number of categories.

5.1. Increasing the cycle top temperature

The heat sources used in power generation, such as fossil and nuclear fuels, solar energy, and at some locations even geothermal energy, are capable of providing the heat at temperatures much higher than the ones used in current practice, which are about 600 °C for Rankine cycles, 1300 °C for Brayton, and intermittent low-duty peaks of 2000 °C in internal combustion engines. Raising of the top cycle temperature is gradually being accomplished by the development of new materials that can withstand these temperatures and associated pressures, by improved cooling technology, and by the development of systems which are less vulnerable to such environments by virtue of their design, such as the use of stationary, in lieu of moving, parts [3]. The observed rise in operating temperature is, however, relatively slow, of the order of just a few °C/year over the past 10 years or so, and, furthermore, the corresponding increase in efficiency is asymptotic.

5.2. Lowering the bottom temperature

Thermal power plant efficiency increases as the bottom (heat sink) temperature is lowered. In the temperature range of ambient coolants, an efficiency improvement of up to about 1/2% is obtained from each °C by which the bottom temperature is lowered. It is thus desirable to seek ways to do so, and a few are described below.

One well-trodden path is the improvement of heat transfer in the heat rejection equipment, most prominently in the power plant condenser. This lowers the condensation temperature and pressure of the steam by bringing its temperature closer to that of the coolant. At the same time this approach increases capital costs and pumping energy use.

An obvious way is to find and use colder heat sinks. Since power station location is presently dictated in large part by the need for some proximity to the users, and by environmental constraints, the selection flexibility as well as the existing differences between the available conventional coolant sources are rather small. At the same time there potentially exist at least three low-temperature heat sinks for thermal power plants which deserve consideration: the cold water in the depths of the oceans throughout the world, the cold air, water and ice in the polar regions, and space.

There are many locations around the world, even near the equator, where ocean water temperatures are down to about 5 °C at depths below about 500 m. After accounting for pumping losses, the use of this water for cooling the power plant condenser is expected to raise plant efficiency by at least 10%. Several experiments of ocean-thermal energy conversion (OTEC) have demonstrated that the construction of the piping system to these depths, and the pumping of the cold water to the surface, are feasible and within reasonable cost. Remaining issues that must be more definitively resolved are environmental impact, including effects on the ocean flora and fauna, temperature increase of the ocean water, releases of CO_2 from the deep water raised to lower-pressure surroundings, and robustness of the piping system under storm conditions.

Power generation efficiency could be significantly increased by using the cold air or ice of the polar regions as coolant. To take full advantage of coolant temperatures much below the freezing point of water, other working fluids would have to be used. In considering this approach, some of the major obstacles to be overcome are environmental impact and, if fossil fuels are used, the problems of transporting them to such sites.

The use of space as the heat sink for power plants is very appealing. Being near absolute zero temperature, it is indeed the lowest attainable temperature heat sink. Having immense (and ever expanding...) size, it would be affected negligibly by any heat addition from the power generation systems located in it. Also, diversion of the power-generation-related energy emissions from the terrestrial sinks to space would serve well in healing our environment and preventing its further deterioration. This is further discussed below.

5.3. Combined power cycles

The main rapid progress in conventional power generation is in the development and use of combined power cycles, using a Brayton topping cycle and a Rankine bottoming one, with efficiencies in the 60% range [4]. Such modern cycles also incorporate technologies for the reduction of NO_x and SO_x emissions. An example [5] is a system in which combustion of a fuel-rich mixture of compressed air and fuel takes place in a burner, the hot gas containing unburned fuel expands though the high-temperature turbine, and is then recompressed and passed on to a second, lean-mixture burner. The gas is then expanded though a lower-temperature turbine and then used to generate steam in the boiler of the Rankine cycle. This rich–lean combustion is intended to produce low NO_x. Because of the possibility of reaction control in the topping part of the cycle, the authors have called it a "chemical gas turbine" cycle. Efficiencies of up to nearly 70% when top temperatures of 1773 K were assumed have been predicted.

Other hybrid cycles for power generation and transportation purposes are described in [6–8].

6. Direct power generation systems

These are devices producing electricity directly from some other type of energy input, such as thermal (e.g., the Seebeck thermoelectric generator, widely used in producing electricity in satellites), mechanical (e.g., piezoelectricity, MHD), chemical (e.g., the fuel cell, batteries), and photon (e.g., the photovoltaic cell). Any thermodynamic driving force can directly generate electricity, and the actual way to do it, and do it economically, is a function of the designer's ingenuity. A review of direct energy conversion methods is given in [9].

Power generation schemes which do not need heat as a primary input are not subject to the Carnot efficiency limitations. Importantly, this bypasses the obstacles associated with trying to attain high top and low bottom temperatures for increasing the efficiency. Classical examples of such devices are hydro-power plants, and water-current or wind turbines. More novel devices are photovoltaic cells, fuel cells, and battery-like devices which generate energy due to solution concentration differences across a semi-permeable membrane (cf. [9]).

Photovoltaic energy conversion has seen rapid progress since its invention in the early 1950s, with conversion efficiency of laboratory units reaching 35%, drastic improvements in stability, and reductions of cost and weight.

Significant progress is also being made in the development and use of fuel cells [10], and topping cycles using them [11–13] which may reach overall efficiencies of about 62% are under development.

7. Space power systems for terrestrial use

Roughly, the average solar power input to earth is 8.6×10^7 GW. Assuming an overall 10% conversion efficiency for solar electric systems, and a global, highly interconnected system of solar power generation stations, about 7.5% of the Earth's surface would be needed to accommodate the projected electric demand in the year 2100, only 100 years from now. Considering the accompanying increased demand for space for the increasing population, and the growing need for power in the years after, this is probably an unacceptably large Earth surface demand even if ocean surfaces are included.

In view of the rising demand for energy, and of the diminishing fuel and available area, the use of space for power generation from solar or nuclear sources seems to be inevitable [14–26]: (1) it allows highest energy conversion efficiency, provides the best heat sink, and relieves the Earth from the penalties of power generation; (2) the costs of launching payloads into space and those of energy transmission are declining.

The major obstacle is the exorbitantly high cost, which under current conditions requires the reduction of space transportation costs about a hundredfold: to less than $220/kg into orbit, for competitiveness. 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.

Much R&D would be needed to overcome these obstacles. Some of the primary subjects are (1) alternate propulsion processes which require less energy, produce 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, and (8) effects of space transportation and power transmission on the atmosphere. 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 [26,27].

Future generation of power in space for terrestrial use will require massive resources and a long time. National and international work on this subject should be invigorated so that humankind will continue to have the energy it needs for its survival and happiness.

8. Micro power systems

There is an increasing interest in the construction and use of very small, of the order of 1000 μm, power generation systems for various applications, ranging from the military to the medical. Since the power produced by such devices is of the order of mW 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 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.

Micro power generators pose very interesting research [28], development, and construction challenges, many related to the very complex flow, transport, and thermodynamic phenomena, where continuum theory often cannot 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 micro power generators in many known and yet unknown applications make the challenges associated with their development very worthwhile.

9. The role of exergy analysis

It is increasingly recognized, and included in practically all textbooks on thermodynamics and energy systems design [29,30] that exergy (or second law) analysis must be added to conventional energy accounting analysis during the conception, analysis, development, and design of such systems. Only exergy analysis can identify the specific irreversibilities and is uniquely required to provide the guidance needed in this process. The application should be implemented in every phase of the project [31]: concept feasibility analysis, detailed system configuration and composition analysis, and the final total system configuration and options for improvement. The first phase requires only a rough evaluation as to whether the proposed system satisfies the second law of thermodynamics. "Finite-time" or "endoreversible" thermodynamics, which has produced an inordinate amount of interest and number of publications, and strong criticism [32], may be helpful in that initial phase, but in that phase only. Since it deals only with extrinsic irreversibilities (and very simplistically at that) and ignores the intrinsic ones that are of major importance in evaluating system performance, it is of no value in the later development phases.

Most of the exergy analysis is nowadays conducted on the third phase of system development, by evaluating the exergy values and changes of component input and output streams and energy interactions. While this can indeed identify the exergy destruction in a system component, it does not deliver the detailed information about the specific process phenomenon, often space and time dependent, which causes the exergy changes. This type of detailed analysis (cf. [33]), due in the second phase of system development, is invaluable in accelerating the evolution of the innovative power generation systems needed to meet the difficult demands of the coming century.

Exergy analysis also serves as an excellent basis for economic analysis [34,35].

Relatively simple examples of such analysis, primarily from the work of the author and his co-workers, are briefly summarized below. A few additional examples are contained in the references of the quoted papers.

9.1. Combustion [36]

Past studies of fossil-fuel power stations have revealed that exergy losses associated with boiler operation are highly significant. Conventional combustion is the most inefficient process in fossil-fuel plants, consuming about 20–30% of the useful energy (i.e., of the exergy) of hydrocarbon fuel. Heat transfer from the high-temperature product gases to lower-temperature working fluid destroys another 15% of the fuel's exergy; 5% of the useful energy of fuel is typically expelled with the flue gases. In other words, combustion, heat transfer, and flue gas expulsion within/from the steam generator are responsible for over 83% of the irreversibility which occurs during fossil-fuel plant operation.

In [36] the exergy changes of the subprocesses of heat transfer, mixing, reaction, and diffusion associated with combustion of hydrogen and methane were analyzed by assuming a number of alternative hypothetical process paths. It was found that the heat transfer between the reacting gas and the surrounding colder gas creates up to 80% of the overall exergy destruction in combustion, with the other subprocesses contributing a few percent each.

9.2. Fuel cells [10]

In fuel-cell chemical reactions the repositioning of the associated electrons is achieved with greater control than in combustion. In the process, a portion of the electrochemical energy of electron bonding is extracted electrically rather than being totally dissipated into thermal energy (i.e., into random motion of the reaction components) as in combustion. Thus, there is less associated entropy production than in ordinary combustion, where electron energy is not exploited and the amount of entropy production is left unconstrained.

Inasmuch as the rate of entropy production ($\dot{S}_\mathrm{p}$) in a process is

$$\dot{S}_\mathrm{p} = \frac{1}{T}\dot{R} \times [\text{driving force(s)}], \tag{1}$$

where T is the absolute temperature and $\dot{R}$ is the process rate, to reduce entropy production for a fixed process rate one must either increase the local temperature or reduce the relevant thermodynamic driving force(s). In turn, the rate of useful energy destruction, $\dot{A}_\mathrm{d}$, is directly proportional to the entropy production rate

$$\dot{A}_\mathrm{d} = T_\mathrm{o}\dot{S}_\mathrm{p}. \tag{2}$$

By reducing process irreversibilities, device and system efficiencies are improved.

In ordinary combustion, a fuel is brought in direct contact with oxygen to react and produce oxidation products. The result is a conversion of chemical energy of the fuel to thermal energy of the products [36], in which, as mentioned above, 20–30% of the fuel exergy is destroyed, and approximately 80% of the combustion irreversibility occurs during the internal thermal energy exchange subprocess.

When a fuel is burned in air at the rate $\dot{R}_\mathrm{f}$ the driving force for the reaction is the difference between the chemical potentials (μ) of the reactants and products, which is the chemical affinity (λ) of the reaction. The rate of useful power consumption by fuel oxidation is

$$\dot{A}_\mathrm{d} = T_\mathrm{o}\dot{S}_\mathrm{p} = \frac{T_\mathrm{o}}{T}\dot{R}_\mathrm{f}\lambda = \frac{T_\mathrm{o}}{T}\dot{R}_\mathrm{f}(\mu_\mathrm{fuel} + \mu_\mathrm{oxygen} - \mu_\mathrm{products}). \tag{3}$$

Fuel cells lower the reaction affinity by first passing ions through an electrolyte. For example, solid oxide fuel cells operate with oxygen ions migrating through a solid electrolyte. By passing oxygen through the solid electrolyte prior to fuel oxidation, such a fuel cell lowers μ_oxygen, which, in turn, lowers the power consumption of the oxidation reaction, i.e., the electrochemical potential of oxygen at the anode (where the oxidation occurs) is lower than the value sensed in ordinary combustion, namely the value in the air free stream on the cathode side of the electrolyte.

After passing oxygen through the electrolyte, the fuel oxidation is less violent (less dissipative, less irreversible) inasmuch as the force driving the reaction λ is reduced.

When heat is transferred, the rate of useful power consumption by heat transfer is

$$\dot{A} = -\frac{T_o}{T}\left(\varepsilon\frac{\nabla T}{T}\right), \tag{4}$$

where ε is the thermal energy flux. By extracting electrical energy during the overall reaction, the energy of the reaction products is reduced. In turn, the temperature gradient between the reaction zone and the neighboring zones is lower than that sensed in ordinary combustion. Thus, relatively less exergy is destroyed during the internal thermal energy exchange.

A benefit of fuel-cell topping systems is the reduction of exergy consumption in subsequent combustion, downstream of the fuel-cell unit in the boiler combustion chamber. This reduction is a consequence of a reduction of the average chemical potentials of oxygen and fuel because they are more dilute after partial oxidation in the fuel cells.

Consider the relationship

$$\mu_i/T = g_i(T,P)/T + \Re \ln \chi_i, \tag{5}$$

for ideal gases, where χ_i is the mole fraction of component I and $\Re$ is the universal gas constant. It can be seen that at a given T, as χ_i is reduced for reactants and increased for products, their μ_i/T values are reduced and increased, respectively, with the effect of reducing the value of λ/T. So, if part of the fuel oxidation has been accomplished in fuel cells, thereby decreasing the χ_i of the fuel and oxygen and increasing the χ_i of the products, the value of λ/T at the onset of the subsequent combustion in the boiler is lowered. Since λ/T goes from the initial value to zero as the combustion proceeds, the effect is then to reduce its average magnitude during combustion and, from Eq. (5), to reduce the exergy destruction. This conclusion is based on the assumption that the temperature of the reactants prior to combustion is essentially the same as in ordinary boiler combustion.

Based on the discussion above, this type of configuration reduces the investment in fuel cells because they are thereby used only while the chemical driving forces are still high. Instead of continuing the oxidation process with increasingly diluted reactants, which produces concomitantly decreasing power yield, the diluted reactants are fed to the combustor, where they combine more efficiently. It is not implied that this plant configuration is either the most efficient or most economical, but it is a simple example which serves to illustrate the improvement to thermodynamic efficiency when incorporating fuel-cell units into electrical power-generating or co-generation plants.

9.3. The nuclear fuel cell?

Nuclear power plants operate at a thermal efficiency of about 29–35%. Therefore, overall efficiency of electrical power generation may be improved considerably by first understanding and then reducing irreversibility of nuclear power plant operation.

In comparison with fossil-fuel plants, the fission process replaces combustion to produce the required high heat for transfer to the working medium of the steam power cycle. In the case of nuclear power stations, there has been little effort directed at the evaluation of exergy destruction within these plants. Siegel [37], employing relations developed by Pruschek [38], performed a second law analysis on a steam-cooled fast breeder reactor plant designed in Germany. He found that the largest exergy loss by far occurs in the reactor itself.

A second law analysis was performed by the author and his co-workers on an operating 1145 MWe BWR nuclear power station to evaluate plant and subsystem irreversibility [39]. The results disclose 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. Plant efficiency and effectiveness are found to be 34.4%, which is well below the 40–45% efficiencies of typical fossil-fuel-fired power generating stations.

Based on these well-known numbers, and the results of the exergy analysis, one recommendation is to give attention once again to the integration of fossil-fuel-fired superheat/reheat units located downstream of the reactor vessel. This modified plant configuration would not only improve efficiency by raising the top operating temperature, but is also anticipated to reduce irreversibility associated with heat transfer in the steam generators. Such an analysis is shown in [40].

A much more profound conclusion stems from a fundamental examination of the nuclear reaction itself. Most of the energy produced during the breakup of the nucleus in the fission reaction and in the joining of nuclei in the fusion reaction is in form of kinetic energy of the produced particles. In a short time and space this valuable mechanical energy, which is pure exergy, is converted into heat as the particles slow down. Even if energy is fully conserved in this slowdown process, much of the original exergy is destroyed, the more so since the top temperatures of the working fluid are severely limited by the safety limits of the fuel rods in the fission reactor and of the fusion system as a whole in a fusion reactor. It is thus obvious that if the original kinetic energy of the fission or fusion products could be used directly to produce electricity, akin to an electromechanical nuclear generator, or produce mechanical power directly, this exergy destruction would be eliminated and a much more efficient conversion of the nuclear energy to power may be attained. Similar to past discussions by the authors on the reduction of combustion irreversibility [36], one alternative means to improve the exergy efficiency of nuclear reactions and heat transfer within the reactor would be to devise fission and fusion processes which would include generation of useful work before the particles are slowed down. For example, if a system could be devised which would operate as a *nuclear fuel cell*, the nuclear reaction and reactor heat transport irreversibilities would be reduced. Work on a thermodynamic foundation of nuclear reactions is under way [41,42], and a proposal, yet untested, to produce electricity by ionization of rare gas atoms with fission fragments, accompanied by separation of the generated positive and negative ions by means of an electrical field, was made recently, in a somewhat vague manner, in [43].

10. Conclusions and recommendations

While the continuing improvements in conventional power generation technology should not stop, the 21st century should see much more devotion to unconventional frontier approaches to that problem, obviously with proper attention to the accompanying environmental, economic and societal issues. The development of new economical materials and devices would allow design of thermal power plants for operation at higher temperatures and efficiencies, but emphasis should be placed on direct energy conversion, i.e., exergy-efficient processes which are neither Carnot limited nor accompanied by large thermal and species emissions. Among these processes, some of the most appealing at present are direct conversion of solar radiation to electricity, and fuel cells. Devices for these are rapidly declining in price, headed for competitiveness with other power generation schemes, and increasingly used in appropriate commercial applications.

Direct conversion of fission and fusion energy into electrical or mechanical power deserves much attention, especially if the nuclear waste problem is resolved in a definitively satisfactory manner.

The use of space for power generation seems to be inevitable: it provides the best heat sink and relieves the Earth from the penalties of power generation. The costs of launching payloads into space and those of energy transmission are declining.

In the interim, more efficient production of power from low-temperature sources, such as solar and waste heat, co-generation, low-emission combustion systems, exploration of hydrogen as fuel, and significantly safer nuclear power production must be pursued.

Since solar energy is an inexhaustible and nonpolluting source which does not alter the global thermal balance, cost reduction in solar power production should be pursued ardently.

Exergy analysis is very helpful in effective development of the innovative power generation necessary for satisfying our needs in the 21st century, and should increasingly and in detail focus on the intrinsic processes in the power generation systems.

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