THE CURRENT STATUS AND POSSIBLE SUSTAINABLE PATHS TO ENERGY "GENERATION" AND USE

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ABSTRACT

The energy predicament that the world faces, composed of rising energy and overall resources consumption alongside with associated rise in negative environmental, economical and social impacts, is described with recent data. A brief discussion of the status, sustainability (economic, environmental and social impact), and challenges and prospects of fossil, nuclear (including nuclear water desalination) and renewable energy use, and of power generation including the further-future concepts of superconductors, nuclear fusion, and power generation in space for terrestrial use, is presented. Comments about energy conservation and the rebound effect are brought up. Ways to resolve the problem of the availability, cost, and sustainability of energy resources alongside the rapidly rising demand, are discussed. The author's view of the promising sustainable energy paths to the future, and last year's trends in government funding, are presented.

1. EXECUTIVE SUMMARY OF THE MAJOR FACTS AND PREDICAMENT (the main sources for uncited information in this section are [1-15], and those cited in further sections of the paper).

1.1 Critical global information.

Energy resources and consumption are intimately related to environmental quality and other vital resources such as water and food. The energy situation must be viewed in that context, and some of the related key global data are therefore shown in Table 1.

1.2 Energy consumption and resources.

- The world primary energy use has been rising each year (excepting a few temporary dips, the most recent one from 1979 to 1983, due to sharp increase in energy price driven at that time by OPEC) and rose by 1.4%, in 2008. The increase *rate* is dropping, due to rising prices, the recent economic downturn, and increases in energy efficiency, but is likely to rise again soon with the economy, as the large developing countries in Asia keep improving their standard of living, China's rose by 7.2% (lowest since 2002), India's by 5.6%, and some significant drops are those of the EU -0.56%, Japan -1.9%, US -2.8%, and led by Australia -4.2%.
- Notably, the reserves-to-production ratio (R/P) remains during the past quarter of a century rather constant (Fig. 1): ~40 for oil, ~60 for gas, and 120+ for coal, and mostly rising! Contrary to imminent "peak oil" predictions and warnings that was to occur as early as the beginning of this millennium, and despite the rise in consumption, the rising prices of fossil fuels and the increasing concern about their availability have apparently also intensified and improved fuel exploration and discovery. There probably exists sufficient oil and gas for this century and coal for 2 or more.

Table 1 Some key data during the period 2006-2008

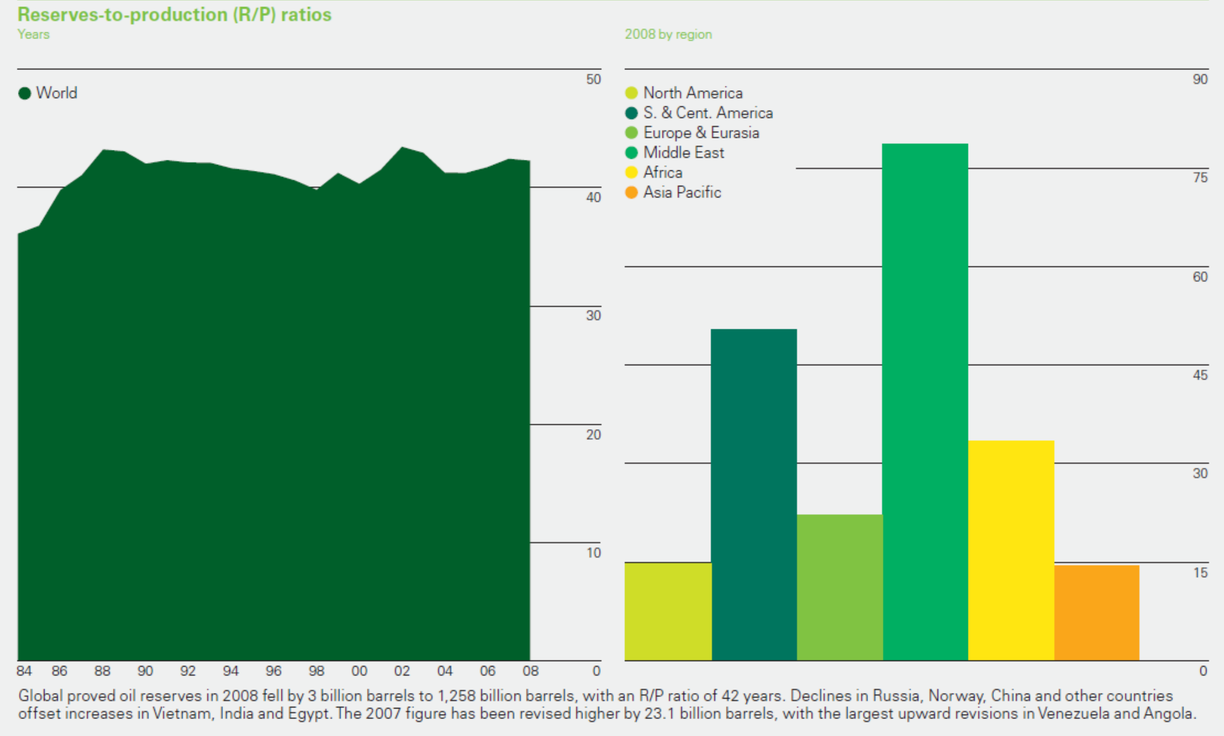
Item	Global amount
Total primary energy use	**473 EJ [1]**[*]
Industry	**19% [13]**
Transportation	**19% [13]**
Residential, services, agriculture	**24% [13]**
Electricity	**38% [13]**
Electric power installed	**4.4 TWe [13]**
Electricity generated per year	**20.2 PWh = 73.2 EJ**[**] **[3,13]**
People without electricity	**1.9 billion**
Global temperature rise in industrial period	**0.76°C, exponential rise**[***] **[13,14]**
Water shortages	**900 million people lack safe drinking water,** **2.5 billion people have inadequate access to water for sanitation and waste disposal,** **Ground water depletion harms agriculture [15,16]**
Food shortages	**1.02 billion undernourished people (1 in 6) [17]**

[*] 4% lower than the IEA [13] value

[**] Indicates a 53% power plant capacity factor

[***] The temperature increase per decade is more than twice as fast as that observed over the preceding hundred years.

- Tar sands, oil shales and gas shales are becoming more attractive and are available in quantities probably exceeding those of conventional oil and gas, but their commercialization is currently associated with severe environmental impacts.


Reserves-to-production (R/P) ratios

Global proved oil reserves in 2008 fell by 3 billion barrels to 1,258 billion barrels, with an R/P ratio of 42 years. Declines in Russia, Norway, China and other countries offset increases in Vietnam, India and Egypt. The 2007 figure has been revised higher by 23.1 billion barrels, with the largest upward revisions in Venezuela and Angola.

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

- Nuclear power produces 14% of world electricity; the number of reactors is increasing very slightly; public perception is improving, new government initiatives started, but the same problems remain. Recent stoppage of the development of the Yucca Mountain long-term nuclear waste storage facility in the U.S. is a serious setback.
- Renewable energy can satisfy at least two orders of magnitude more than the world energy demand, but negative impacts aren't inconsequential (see Section 2.6).
  - Wind and solar photovoltaics (PV) are experiencing an exponential growth as costs decrease;
  - While wind power price is reaching parity with fossil fuel power, solar power is still at least twice as expensive
  - The very large areas and materials types and quantities required by solar, wind, and marine power bring up major sustainability concerns
  - Interest is renewed in solar-thermal power.
  - Geothermal energy deserves more attention.
- Strong subsidies for converting food to fuel are increasingly proven to be a mistake, helping triple the price of foods and reducing their availability, and raising water consumption, all as predicted by some ahead of time
- While hydrogen and fuel cells continue to be valuable in the energy portfolio, they have not met the expectations expressed by the huge R&D investments made by many governments. This could have been foreseen by more careful early analysis, and some of the moneys and valuable scientists' time could have been spent better.
- The plug-in electric or hybrid car seems to be the preferred route to private transportation. Improvement of traffic management, roads, and public transit are at least as important but don't receive adequate attention.
- Fuel and energy consumption in general must be significantly constrained, with due attention to prevention of the rebound effects; Pursuit of higher efficiency without care of the rebound effect is counterproductive.

1.3 Environmental and food impacts of energy.

- Global temperatures are rising over the past 50 years on average at an unprecedented and exponential rate, alongside with similar rises in greenhouse gas emissions; there is clear evidence of major melting of polar ice caps, glaciers, and snow caps.
- The water and food supply are in crisis, with about 1 in 7 people lacking safe drinking water and 1 in 6 being undernourished (Table 1).
- Energy and water use are strongly interdependent.
- Conversion of food to fuel endangers the food and water supply and raises their price
- The "Living Planet Index" is estimated to have declined since 1970 by about 30%, and the "Ecological Footprint", increased 2.4-fold in the same period (cf. [18}): we seem to be <u>running out of environment much faster than out of resources.</u>

1.4 Future electric power generation.

- A most imminent challenge is that expected demand for electricity would require during the coming two decades the installation of as much power generation capacity as was installed in the entire 20th century.
  - One 1000 MW plant every 3½ days
  - e.g., China is adding already one coal-fired 1000 MW plant each week
- The global electric energy generated growth in 2008 was 1.3%, to 20,202 Terawatt-hours = 73.2 EJ
  - The global growth in 2008 was notably more than 3-fold lower than in preceding years;
  - It dropped in the US by 1.3%, and in EU by 0.1%, rose in India by 2.9%, China 4.5%.
- While the plug-in hybrid electric car and electric-driven public transportation seem to be the most promising ways towards energy-efficient transportation, but this would further raise the demand for electricity in a most significant way, perhaps doubling it.
- Because of its abundance in the most energy consuming countries such as China, the USA, parts of Europe, India, and Australia, and the currently relatively low cost of power generation when using it, coal is likely to be increasingly the main basic fuel for power generation, partially after conversion to gaseous or even liquid fuels, with the reduced emissions IGCC (Integrated gasification combined cycle) plant receiving major attention
- The combined cycle power generation plants are the most desirable, having efficiencies of up to about 60% even at present, less emission than other plants when using natural gas, and reasonable cost that would keep decreasing as the technology advances further.
- The technology for CO_2 capture in fossil fuel power generation is within reach, but sequestration of the CO_2 is not yet
- Despite the unresolved problems of waste storage, proliferation risk, and to some extent safety, nuclear power plants are likely to be constructed at least for special needs, such as countries that have much better access to uranium than to fossil fuels, and if carbon emissions become costly. The amount of uranium-235 in the world is insufficient for massive long-term deployment of nuclear power generation; nuclear will be sufficient if breeder reactors are used, but that technology isn't safe and mature enough and is not likely to be in the next couple of decades.
- Wind power generation will be continue to be deployed rapidly and massively, but will be limited to regions where wind is economically available, and will be limited by the extent and quality of the electricity distribution grid.
- Photovoltaic power generation will continue increasing in efficiency and decreasing in price, and being employed in many niche applications, but being three to five times more expensive now than other power generation methods, and also limited by the extent and quality of the electricity distribution grid, and even by availability of materials, it may not reach parity in the coming decade.
- Geothermal power generation deserves much more attention as a viable and potentially abundant renewable energy source.
- Improvements and technological advances in the distribution and storage of electric power will continue and should be advanced much faster.

1.5 Economic/financial implications

- A major concern (or opportunity?) is that the price of oil was lately growing very rapidly, from $28/barrel in 2003, to $38 in 2005 and occasionally to above $80 in 2006 and peaking at $147 in 2008, but then precipitously dropping to $40 by the end of 2008, and rising again in 2010 (as of February 15) to between $71 and $81.
- The peak price is one to two orders of magnitude higher than the cost of extraction, possibly meaning that financial speculation is overwhelming supply and demand, and all technical improvements.
- National GDP can be increased without increasing energy consumption.
- Globally, costing of energy resources remains inequitable, as it doesn't include subsidies, environmental impact, and other consequences
- The investments in energy R&D appear to be much too low, less than half a percent of the monetary value of the energy use, to meet the future needs.

1.6 Social aspects

- By the years 2050 the world population is predicted to rise by 50% [19]; This estimate is based on the current trend of slowly declining population increase rate, but some populous countries are at this time encouraging their population growth or implicitly allowing it, so the population increase may in fact be much larger. New generations consume on average more energy per capita, than their parents did.
- Many governments of the world are subsidizing energy conservation, development of renewable energy, and reduction of greenhouse gas emissions to some extent. While the intent is very positive, the outcome is not always so because political creation of artificial economies is unstable and misleading, and often not well planned, especially in regard to longer term broader effects.
- Energy's increasingly important role in economics, accompanied by government interventions that are at times not well thought out, and by international strife and competition that ignore global sustainability threats, give rise to massive fraud by entire countries, companies, and individuals, and to breakdown of free markets, as demonstrated for example by the Enron scandal, by the financial systems' bankruptcies that led to the current economic turndown, and by the wildly fluctuating oil prices that are unrelated to supply and demand.

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2. SOME POSSIBLE SUSTAINABLE PATHS TO THE FUTURE

2.1 The sustainable development imperative

In view of the above-described predicament of highly interrelated severe challenges, and indeed dangers, and the massive scale of energy development, it is highly inadvisable, and unlikely, that energy resourcing, conversion and consumption continue to be developed unsustainably. Sustainable activities have many definitions, but simply, ***they describe a logical process that takes carefully into account all relevant consequences within time and space boundaries that are large enough to ensure satisfactory existence for us and other humans, and of our and their descendants***. These "all relevant consequences" are primarily **economical, environmental and social**, the three pillars of sustainable development. In a rigorous sustainability analysis an objective function for optimization is defined based on all of these criteria, they are all assigned appropriate quantitative metrics and relative weights, they are then agglomerated, and the optimal mathematical optimum of the objective function is solved for (cf. [20-22]). Sustainability is only emerging as a science, and must be developed and applied urgently.

2.2 Energy "conservation"

The first step in any path to the future is wiser use of the energy resources, also referred-to as conservation. This would include elimination of obvious waste, higher energy conversion efficiency, substitution for lower energy intensity products and processes, recycling, and more energy-modest lifestyles. Conservation is typically also the easiest and cheapest to implement. At the same time, it must be implemented in a way that does not deprive people from the basic necessities and comforts of life, nor has a very negative impact on productivity. In pursuit of higher energy efficiency one must also realize that the inevitable "rebound effect" tends to increase consumption and create other negative outcomes (such as more cars on the road, for example) (cf. [23,24]). This requires that improvement of energy efficiency should be accompanied by commensurate demand-side management.

2.3 Clean coal

Since coal is abundant (especially in some of the highest energy consuming countries, such as the USA, China, and India, with the latter two having little fluid fossil fuels), rather familiar for power generation and typically produces the cheapest electricity, and less subject to political and commercial pressures than fluid fuels, it is expected to increase its share of the World's total primary energy to beyond the current 29%. This trend is expected despite the many problems with coal use, not the least being its regrettable supremacy in the specific global warming emissions.

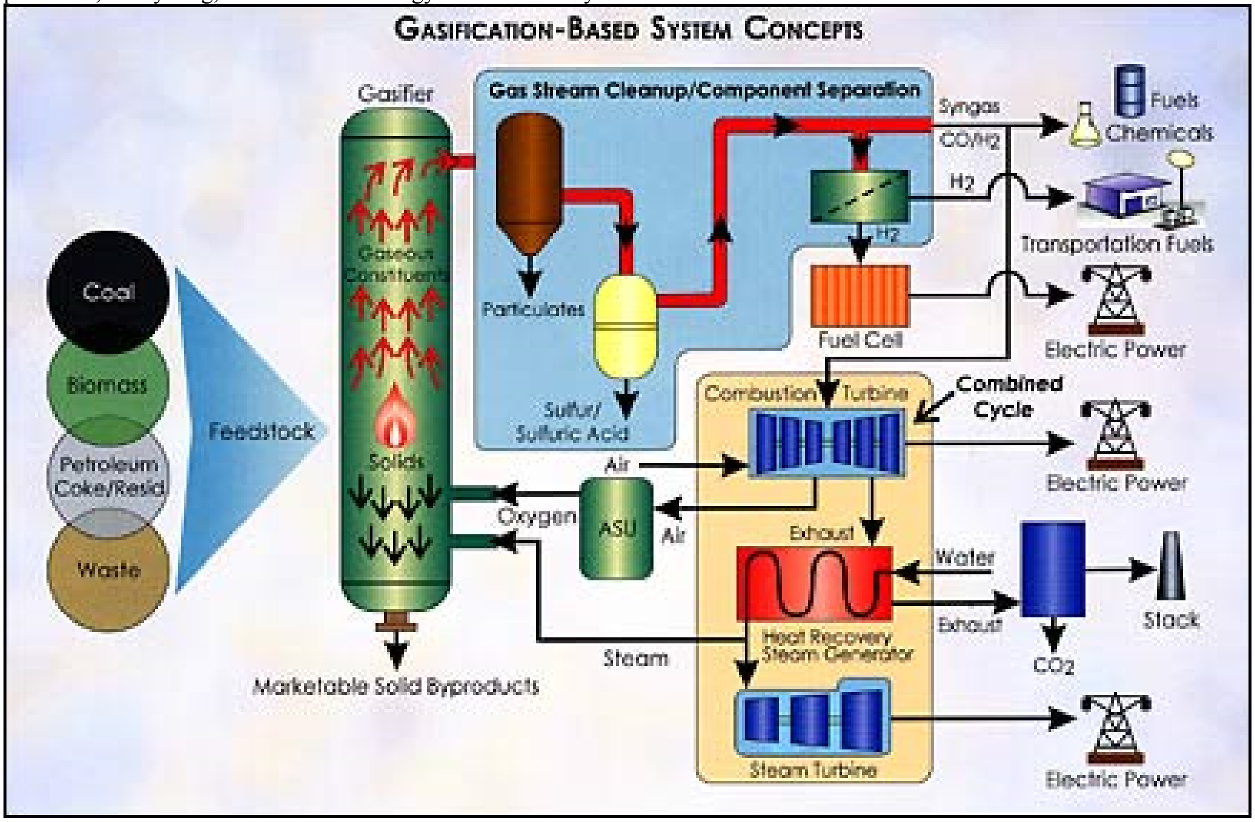

Fig. 2 *A typical solid fuel IGCC [25]*

Much effort is devoted to "clean coal" power generation, in which the emissions of all harmful pollutants are to be reduced and the efficiency of power generation increased. In the past, the major emissions control effort focused on SO_x, NO_x, mercury and particulates, with reasonable progress, but concerns about global warming have for the past decade added the inclusion of CO_2, which is emitted in quantities that are about 6-7 orders of magnitude higher than those of the other pollutants.

Being a solid fuel, coal is much more difficult to transport and use than fluid fuels, and is also practically unsuitable as a direct fuel for most vehicles. Consequently, another R&D direction is the conversion of coal to fluid fuels, such as synthetic gas (Syngas, typically hydrogen and CO) or some form of liquid petroleum.

Among the most promising approaches for coal power generation that also may attain the best combination of CO_2 capture, high efficiency, syngas production, and reduction of other pollutants to tolerable levels is the integrated gasification combined cycle (IGCC). A flow diagram of such a plant is shown in Fig. 2. Reduced emissions IGCC plants, increasingly with CO_2 capture (CC), are thus likely to be receiving major attention: there are about 160 commercial projects in operation/ constructions/design, 450 gasifier vessels, production of 68,000 MW thermal energy and of 430 million normal cubic meter per day of syngas [26,27]. Intensive efforts are made for the adoption and development of this technology in the Asia-Pacific region (cf. [28,29]), but the worldwide progress to commercialization is still slow, mostly hindered by cost and insufficient incentive.

The current overall IGCC power generation efficiency is slightly above 40%, predicted to rise to 60% with additional R&D, and the capital cost is currently estimated to be double to triple of conventional coal fired power plants. The USDOE goals [5,25] are to complete by 2010 the R&D for advanced IGCC coal power systems that have 45% to 50% electrical efficiency at a capital cost of $1,600 per kW (in constant 2007 dollars) or less. This time-goal appears to be much too optimistic, especially due to difficulties in the gasification part, and is more likely to be attained in 5 to 10 years if the program is pursued vigorously.

The extensive use of coal will increase the need for more stringent mining and emissions controls and attention to other ecological and social problems associated with a coal economy.

It very noteworthy that while the technology for CO_2 capture is within reach, sequestration of the captured CO_2 is still far from being available in some robust form.

In summary, "clean coal" power generation is a most important approach for at least the coming half century, and poses many interesting and challenging opportunities for engineers and scientists in all its aspects: exploration, mining (including social aspects of human labor), processing, environmental care and remediation, transportation, storage, combustion, emissions, and power generation.

2.4 Tar sands, shale gas, and shale oil (cf. [30-35])

These fossil fuel sources are much more difficult to exploit and have much more serious environmental consequences than conventional fossil fuels, but must be considered when discussing the depletion of oil and gas, since they are extremely abundant. Just the tar sands of Canada and the oil shales at one location in the U.S. are each estimated to have more exploitable oil than the entire OPEC reserves. Shale gas has been used in small quantities for more than a century, but new technology and higher gas prices have revealed very large resources in the US, that together with other natural as resources is predicted to satisfy the US, at current consumption rates, for the next hundred years [35].The process of converting tar sands and oil shales to fuels consists of mining the solid, retorting it, and further processing by distillation. Shale gas is released by hydro-fracturing from shale formations in which it is trapped. All these fuel resources are also available in many other countries.

Both mining and processing of these fuels generate greenhouse gas emissions; they disturb the mined land, generate large quantities of spent ore, use much water, and impact regional air and water quality. The total energy and water requirements together with environmental and monetary costs have made production uneconomic in the past, but Canada is currently producing about 1.3 million barrels/day of oil from tar sands, reportedly economically competitive when oil price is higher than about $50/barrel. In this price comparison it is unclear whether all of the externalities have been considered fully.

Fascinating engineering and scientific challenges exist in all phases: mining, conversion to fuel, and especially in reduction of water use and of other negative environmental impacts.

2.5 Nuclear (fission) energy

In 2008 there were 436 nuclear power plants in operation (7 less than in 2006) with a total net installed capacity of 370 GW(e), and producing about 14% of the world's electric power. 5 nuclear power plants are in long term shutdown, and 56 nuclear power plants (52 GW) are under construction [9]. The capacity factor of nuclear power plants has been increasing, reaching a remarkable average of 92% in the U.S.

A major current driver for the use of nuclear power is the potential to alleviate global warming. While somewhat controversial both politically and factually, most of the available archival and authoritative sources agree that nuclear power produces, per unit power generated, only about half the CO_2 of wind power, 1/10 of solar PV and 30 fold less than natural gas (cf. [9,36-45]). Even the study that predicts the highest CO_2-equivalent emissions of nuclear power generation as compared with all the other cited sources, at an average of 65 g CO_2-e/kWhe, that would make nuclear power emissions about twice as intensive than those of wind power, shows a wide range of 10 to 130 g CO_2-e/kWhe [45], where the lower end supports what most sources claim. The accuracy of the predictions depends strongly on the comprehensiveness of the life cycle analysis and on the various conditions and assumptions for the sub processes in it. It is generally expected that the emissions will drop with improved technology of the entire cradle-to-cradle process. One simple example, out of many, is that new uranium enrichment technology in use requires only about 1/20 of the energy needed with the older diffusion systems.

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

Geological storage of high level nuclear wastes is facing a strong public opposition, particularly because of the extremely long time, of the order of tens of thousands of years, or a million years according to a recent USEPA proposal [46], needed for its surveillance and monitoring. In fact, the new U.S. administration has decided this year to stop the development of the only planned long-term nuclear waste storage facility, Yucca Mountain, thus creating a serious setback to large scale nuclear power development till a new solution is found. A more reasonable method of dealing with this problem, if commercially feasible, is partitioning and transmutation of the long life radioactive elements, currently considered to be done either in accelerator driven systems or in proposed critical reactors.

To respond to some of these problems, there are world-wide efforts to develop the "Generation IV" nuclear reactors [47-49] (with a target date of 2030) that would have the following main attributes: electricity price competitive with natural gas (3 US c/kWh), capital cost of $1000/kW, construction time of 3-4 years, demonstrated safety to regulatory agencies and to the public, and proliferation-resistant. These goals are positive but appear to be unachievable in that time frame without huge investments, if at all, which, if made, would diminish other energy development efforts. The main Generation IV advanced nuclear reactors considered are the sodium-cooled fast reactor, molten salt reactor, supercritical-water-cooled reactor, lead-cooled fast reactor, very high temperature reactor, and the gas-cooled fast reactor [49].

Another serious problem is the possible scarcity of uranium for massive increase in nuclear power generation, if that power continues to be generated based on U-235. While there are many claims that U-235 is abundantly available, calculations based on seemingly reliable date [50-53] show that based on a consumption of 180 tons enriched uranium per year by a 1 GWe nuclear power plant, and commercially available U-235 quantities, if 50% of the current world primary energy was produced using U235, it would last for 14 years; If 50% of world electricity at the typical 33% nuclear power plant heat-to electricity conversion efficiency was generated using U-235, the fuel would last for 29 years. This would be proportionally longer if the conversion efficiency was increased. Theoretically, the fuel would last for more than 1000 years if breeder reactors would be used. That could be solved by developing and commercializing breeding reactions that produce fuel without long term wastes, such as those based on Th-232 that is very abundant element in nature. Using Thorium as nuclear power reactor fuel, the released energy for a given quantity of the natural Thorium is more than one hundred times greater than that from the currently used U-235 driven nuclear reaction. In the meantime, efforts are under way to extend the life of current plants to 60 years, from the originally planned 40 years.

Nuclear reactors can also be used in "dual-purpose" or co-generation or poly-generation plants, where in addition to power generation or even without it, the fission heat can be used for various processes that require energy in the form of heat, such as water desalination. Fossil-fuel fired dual-purpose plants that simultaneously produce electricity and MSF (Multi-Stage Flash distillation) desalinated water are indeed widely used commercially, and are more energy efficient and economical than separate plants that have a single of these products each. The original dual purpose plants used a Rankine steam power plant for generating electricity, the turbine of which (having an inlet temperature 500-600 °C) was backpressure or extraction for supplying the heat to the desalination plant. Higher efficiency and better economics were obtained in later generation systems using a topping gas turbine (inlet temperature ~1200 °C) with a bottoming back-pressure or extraction steam turbine in a combined cycle (cf. [54]).

Nuclear power plants, currently predominantly pressurized or boiling water reactors, produce steam to drive a Rankine cycle. Nuclear fission heat thus replaces fossil fuels used in fossil fuel fired Rankine power generation systems, and an important difference is that nuclear power plants of this type have a turbine inlet temperature that is below 300 °C while in fossil-fuel fired ones it is up to 650 °C. This results in a significantly lower thermal efficiency of nuclear power plants, below 35%, as compared with ~45% in the fossil-fuel-fired ones (two commercial reactors incorporating fossil fuel superheat to raise the efficiency were built and operated [55,56], and the concept was analyzed by the author thermodynamically and thermo-economically [57]). Noteworthy is the fact that the lower efficiency of nuclear plants also results in their discarding up to ~25% more waste heat that can indeed be used in heat-using processes if the temperature of that heat is compatible with the process. Since the power generation efficiency drops in proportion with the increase in the rejected heat temperature, the possible energy benefits of such a dual purpose plant for a unit of heat input would be moderated by the loss in electric power generation capacity. Nuclear power plants can thus be used in the dual purpose mode to also desalt water thermally, but the relatively low efficiency of the current commercial nuclear plants would make them significantly less energy-efficient than the fossil-fuel fired combined cycle dual purpose plants.

Some of the Generation IV advanced reactor concepts are planned to operate at high temperatures, comparable to those of gas turbine plants, and could therefore also attain dual-purpose performance similar to that of exiting fossil fuel combined cycle dual purpose plants. For example, a recent study [58] of dual purpose plants based on two of these advanced reactor concepts, the gas turbine–modular helium cooled reactor (GT–MHR) and of the pebble bed modular reactor (PBMR) have helium as the working fluid, that must be cooled from ~136 °C to 26°C while rejecting ~300 MWth. The study assumed that the heat will drive a multi-effect seawater desalination plant, ad calculated that alongside with producing the planned 519-600 MWe, the plant will also produce ~40,000 m^3/d desalted water at competitive prices when the oil price was assumed to be 20.62

$/bbl; at current oil prices that are almost quadruple, the system economic viability would be higher if all their assumptions, including that of feasibility and viability of these yet-unbuilt plants, were correct.

At the low temperature end, a few "nuclear heating reactors" (NHR) that just produce relatively low temperature district heating or process heat and no power were built and operated, mostly in the Russian Federation, China, and Canada, because of their simplicity and lower cost, and the advantage of small capacity and size suitable for a city or district, and declaredly to have higher safety. Such reactors are proposed for supplying heat for thermal water desalination plants [59,60] Even if the stated safety advantage may be valid, it is thermodynamically unwise to use the extremely high nuclear fuel fission exergy just to produce low temperature, and hence very low exergy, heat. Even conventional power generation reactors lose half of the original exergy in the process [61].

Like any source of heat or electricity, nuclear energy can indeed be used for water desalination, and a few plants were built and operated (cf. [62-64]). Since there is no specific synergy or antagonism between use of nuclear fission and water desalination, its promotion for that use is driven primarily by the same reasons that nuclear energy is promoted for power use: avoidance of using fossil fuels, much lower emissions of CO_2 and thus mitigation of global warming and possible (but unpredictable) financial carbon credits (cf. [65]), and claimed superior economics. Consequently, the decision on using nuclear energy for desalination is no different than the decision on using nuclear energy for any other application. It is also noteworthy that the energy choice for desalting water is not only between nuclear and fossil fuels, as most of the nuclear desalination proponents, headed by IAEA, claim: desalination can also be performed using renewable energy. The cost of energy from renewable sources is gradually dropping, and several large scale projects, such as DESERTEC [66] for producing electricity and fresh water from solar and wind are in development. Many countries in the Middle East and North Africa are blessed with vast renewable energy resources, alongside with relatively inexpensive and available land; for example [67] just one-twelfth of Bahrain's unused land area would be sufficient to provide its current electricity consumption if solar energy was used to generate the power, and only about 1/24 of the area would be needed if wind was used; only 3.5% of the unused land area in the Kingdom of Saudi Arabia may be needed to provide its entire energy consumption by using just the solar energy.

To summarize, because of the increasing concern with global warming generated from the use of fossil fuels, and because no serious nuclear accidents have occurred since 1986 (Chernobyl), "public perception is improving, but is still not good and people have the feeling that they have to choose between greenhouse effect and acid rains associated with fossil fuels use, and severe consequences of possible nuclear accidents (even though their theoretical likelihood is very low, estimated at 10^{-6} per reactor-year), of nuclear wastes, and of use for warfare and terrorism. According to some opinions, the choice is between the plague and cholera" [68].

2.6 "Renewable" energies: their successful implementation requires a realistic assessment

2.6.1 Introduction. Rather than describing in detail the status and potential of renewable energy sources and uses, this Section focuses on oft-ignored issues of realistic assessment and approach to their successful implementation, and to the somewhat underemphasized potential of geothermal energy. Renewable energies have many clear advantages by being abundant, not depleting the basic energy resource in the time frame relevant to current human interest, being typically less polluting and dangerous, their resources are much harder to own, control and manipulate than fossil and nuclear energy, and are emotionally more comfortable to many who are concerned about excessive industrial and large-corporate dominance. They also therefore have a strong socio-political emotional appeal that unfortunately sometimes tends to discount some of the important problems associated with large scale use of renewable energy. This appeal, ironically, slows rational development of renewable energies and may have negative econo-social impacts. We must seek renewable energy solutions that are sustainable by definition, i.e. economically, environmentally, and socially. Some of the main challenges in massive sustainable implementation of renewable energies, are, briefly, their low energy flux that requires the use of very are areas and quantities of materials, consequent environmental impact, and transience (time-dependence with periods of no availability). While the author strongly favors renewable energy development and use, these challenges and possible methods for trying to meet them are very briefly discussed below.

2.6.2 Low energy flux. Renewable energies such as solar, wind and marine are collected and converted locally, where commercially available, and the overall quantity per unit time for a site is basically the product of the energy flux and the collection area. For example, the terrestrial surface solar energy flux for commercially practical areas is of the order of 500 W/m^2 and never more than about 1,000 W/m^2 because the solar constant is 1,366 W/m^2. Applying a generous capacity factor of 25%, the solar peak power is 125 W/m^2 to 250 W/m^2. After accounting for the solar-to-electric power efficiency that is between 10% and 45%, the actual effective (electricity output) flux is 13 W/m^2 to 113 W/m^2.

For wind power, practical use values are for wind speeds between 7 m/s and 20 m/s (the ''cut out'' speed for the wind turbine). Applying a generous capacity factor of 25%, the wind peak power flux is 30 W/m^2 to 720 W/m^2. After considering the wind-to-electric power efficiency, that is currently 45% at best, the actual highest effective flux is 14 W/m^2 to 324 W/m^2.

To assign these area requirements some comparative value, the power generated by a 1,000 MW coal power plant with a capacity/availability factor of 80% would require a solar collection field area between 7 km^2 and 62 km^2 or a wind turbine interception area between 2.5 km^2 and 57 km^2.

As to hydropower, it has a significantly larger energy flux at the dam itself, but not if the entire river is considered.

Based on energy density and practical fuel flow rates, fossil fuels have energy fluxes that are 6 orders of magnitude higher (cf. [69]). If the extraction/mining areas are included, these numbers obviously drop, but while the extraction/mining area is large, its cost per unit area is relatively small because the amount of needed equipment per its unit area is small.

It is obvious that such very large areas needed for using solar, wind, and marine energies incur large costs even if the energy collection equipment price per unit area is low (the real estate itself and its preparation and maintenance have a significant value), and also have important environmental and social impacts when compared with conventional energy systems. It is important here to include in the analysis the energy and environmental (including resource depletion) effects embodied in the used equipment. This is the classical tradeoff optimization problem: trading the higher specific costs (costs always including all externalities) of renewable energy use against the costs and negative consequences of using fossil and nuclear power sources. Further discussion is presented below.

2.6.3 Transience. All renewable energy sources are associated with some degree of time-dependence, which is most severe both in amplitude and period for solar, wind and marine energy, less severe for hydropower, and least so for geothermal energy. Unlike fossil and nuclear energy supply that can be relatively easily controlled by the producer, renewable energy availability is dictated by nature. The only way that we can control it is by reducing its use from the available maximum, as long as some is available. None is available, e.g., when the sun doesn't shine or the wind doesn't blow. Typical capacity factors (relative to the installed power capacity) for wind and solar power generation systems are between 16% and the optimistic 35%, but usually around 20%. Exacerbated by the fact that energy demand is transient too, this poses a serious economical problem in matching supply to demand. Furthermore, the utility cannot always accept all of the generated power, and the "Infeed Factor", i.e. the fraction of the produced power that can be accepted by the utility at the time of generation, was reported to be about half of the Capacity Factor (cf. [70]).

This challenge has a strong economic impact because of the cost of energy storage that may need to be implemented to accomplish the needed matching, where the renewable energy collection field is made large enough to both supply current demand and charge the storage for use during periods when demand exceeds supply. Technologies are available for energy storage, but they are usually expensive and somewhat complicate system control and operation. For example, heat at low temperatures, such as used for buildings heating, service water, and drying, can be stored reasonably economically in its sensible form in liquids (primarily water) and solids (such as rocks), but heat storage at temperatures above about 200°C is much more difficult, expensive, and not entirely robust for commercial use. Direct storage of large amounts of electricity is uneconomical because batteries are at present too expensive and bulky. Indirectly, it can be stored by converting it to mechanical energy that is then reconverted via turbo-generators back to electricity when needed, but the most economical and proven of such method, pumped hydro storage, depends on geography and water availability, and can be used in only few regions. A very appealing method is "grid storage", in which the electricity distribution grid is extensive enough to allow maximal generation of renewable energy at any time, and its transmission to customers who need it, without using any physical storage at all, or using pumped hydro storage by transmitting the electricity to lo geographic locations where such storage is feasible. An extensive world-wide grid would obviously be ideal for that purpose, if transmission losses are not excessive.

A way used to reduce the transience effect and need for storage is to construct hybrid power plants, where the renewable energy is backed up by conventional fuels, typically fossil but in principle also nuclear. In such plants conventional fuel is used to supplement the renewable-source output to satisfy the temporal demand and/or raise overall power generation efficiency. While this approach adds some operation and control problems (one being the big difference in time need to bring up to load a coal power station and a renewable energy one), it is feasible, used in solar thermal power systems, and was shown to work in the increasingly successful development of solar thermal power (cf.71-81]). At the same time it is noteworthy that this approach requires the construction and operation of two plants, the renewable and conventional, and still retains dependency on conventional fuels and the associated emissions problem.

At present, the transience of renewable energy is considered by some experts (cf. [70]) to preclude its massive implementation and use. Taking wind power for example, it is variable, both over the course of each day and between seasons, and is not easily forecasted with any degree of certainty.

It is interesting to note that if transportation converts largely, as expected, to electric cars, the very large overall storage capacity in the individual car batteries could make this storage available to some extent for better use of transient power sources.

2.6.4 Land demand. As introduced in Section 2.5.2, the diffuse nature of renewable energies like solar and wind require very large surface areas for plants using them, for example a wind power farm at a favorable location and with an annual capacity factor – efficiency combination of 20% (cf. [82]) and using a 100 m diameter 2.5 MW peak power wind turbine would produce about 14 kWh/m^2 per year (the power equivalent is ~ 1.5 MW/km^2). To generate power equivalent to that of a 1,000 MW coal fired plant with a reasonable capacity factor of 80%, a wind farm having land area of 533 km^2 would be required. It is noteworthy that often only the "footprint" of land that has to be taken out of production to provide space for turbine towers, roads, and support structures is included in the land demand, rather than the total area that includes the 3-10 turbine diameters of spacing required between wind turbines. This assumes that the land between the wind turbines can serve some other purpose such as farming. Under such assumption estimates land need of about 1000-2000 m^2 per turbine [83]. This would create a vastly different, and largely unrealistic estimate of about 200 MWe/km^2 (assuming again a 20% capacity+efficiency factor), two orders of magnitude higher than the above-presented number of 1.5 MW/km^2 obtained when the inter-turbine spacing is included. While assumptions of any kind can be made as long as they are well explained and justified, this is a striking example of how the facts could be misunderstood and misinterpreted.

It is also noteworthy that land prices typically increase with time, and if massive deployment of renewable energy takes place, the corresponding very large demand for the required land will undoubtedly affect the real estate market significantly, including the decrease of affordability of housing.

While the large land demand can be alleviated by increasing the capacity factor, this would limit the area of available sites that have such favorable wind conditions, and increase the need for sites remote from electricity users. Other alternatives are designs that increase the power generation rate per unit land area by innovative, aerodynamics based configurations that minimize flow interference between turbines, and placing wind power plants at sparsely populated areas and offshore. Both options incur higher system and transmission costs, and energy losses. Solar power use poses the same challenges, and in either case the huge areas required create significant economic, environmental and social problems.

2.6.5 Environmental impact. It is impossible to avoid significant environmental impacts when using such large land or ocean areas. The local and passing biota are affected, use of large quantities of needed materials incurs environmental costs in their cradle-to-cradle life cycle, shading of land by solar panels, changes in the radiative properties of the earth surface, and effects on natural air currents.

2.7 Geothermal energy

Solar, wind, hydro and biomass energies are on the earth surface while extensive geothermal energy use requires digging to significant depth into the ground. Perhaps because it is “far from sight – far from mind”, geothermal energy does not receive nearly the interest and investment that other renewable forms of energy do, despite some unique advantages. Besides being “renewable”, geothermal energy is abundant, with a long-term potential that is estimated to be more than 200,000-fold of current world energy demand [84-86], it is available at a steady supply rate and is thus much more usable than the intermittent and unsteady wind and solar, its land use is very low: smaller 3-fold than that of wind power generation and 10-fold smaller than solar or coal, and it can have very low or zero emissions of any kind with proper system design [84]. Nevertheless, issues of liquid and gas discharges, proper recharge (to maintain reservoir productivity, dispose of undesirable geothermal fluids and prevent land subsidence), water management, and risk reduction (induced seismicity, etc.) must be taken carefully into consideration in design and operation.

Its current and future use is for heating (including low temperature ground heat heat-pumps), combined heat and power generation (CHP), and power generation. 10 GWe are currently produced worldwide from geothermal energy, and more than 100 years of experience have been accumulated. The electricity currently produced is typically competitive in price, at about 7-10 US ¢/kWh, and readily reducible by half [84,86]. Commercial geothermal wells are currently 60m to 3,000m deep, with the drilling technology borrowing from the extensive experience of drilling for oil and gas (that reach depths of around 6,000m). Since the temperature of the geothermal heat source, whether hydrothermal, dry rock, or magma, increases with the depth, access to massive amounts of high temperature geothermal energy depends on drilling technology. Currently aiming at 10,000m, the temperatures there are 400°C to 600°C at pressures around 1,000 bar, thus having a very high power generation potential, but economical drilling to these depths and conditions is still under development.

2.6.6 Cost

Hydropower and geothermal power are typically competitive in price with fossil and nuclear power. As to other renewable energies, while wind electricity price is becoming competitive in favorable geographic regions (and in many cases under favorable government subsidies of different types), solar power is still about 3-5 fold more expensive than that from conventional fuels. This brings into clear view the need for rigorous sustainability analysis, that evaluates the environmental economic and social costs, and the optimal solution that comes from this set of equations. For example, while the use of renewable energy reduces the environmental externalities, it raises the costs and is thus likely to leave some people hungry, thirsty, or without proper health care, damaging the social aspect of sustainability.

3. SUPERCONDUCTORS (cf. [87,88])

Superconductivity is a phenomenon that certain metals and ceramic materials have no electrical resistance when cooled to very low temperatures, originally at the very low critical temperatures[1] below 17K. Superconductors also exclude externally applied magnetic fields

By 1987, ceramic compounds, e.g., $YBa_2Cu_3O_7$ (YBCO) were developed that had a T_c of 92 K, a very important advancement because it allows cooling by the commonly produced and safe liquid nitrogen, which has a liquefaction temperature of 77K. These materials are called High-Temperature Superconductors (HTS) and have the potential to become a key twenty-first century technology for improving the capacity, efficiency, and reliability of the electric system. For example, they could provide transmission and distribution systems with smaller footprints and much smaller (and more efficient) motors, transformers, and other electric devices.

The USDOE declared in 2009 the following HTS development roadmap:

“By 2012, verify operating characteristics and reliability of high-capacity HTS cables for distribution-level systems and gain industry acceptability and establish design rules based on the full characterization of mechanical and electrical properties of existing and new dielectric materials at cryogenic temperatures,

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[1] Critical temperature (T_c) is the maximal temperature at which superconductivity can be maintained.

By 2020, develop prototype wire achieving 1,000,000 length-critical current (A-m) for second-generation wire."

Intensive work is also ongoing in Germany and Japan

The major foreseen benefits of HTS power applications are:

☐ Electrical energy losses in electricity transmission and distribution are about 10-15% of generation; when implementing superconductors in motors and other electric devices the overall savings are about 20-40%.

☐ Ability to efficiently distribute electricity to higher distances, especially significant for using energy-rich renewable energy sources located in regions of low energy demand

☐ Increased grid reliability and security by providing efficient power interconnections with high capacity

☐ Minimal environmental impact: HTS cables can be readily permitted and installed in dense urban areas

☐ Low-impedance design enables dynamic control of alternating current power flow, alleviating grid congestion

☐ Reduced right-of-way requirements (smaller footprint)

☐ Superconducting fault current limiters do not add impedance to the circuit during normal operation

The man ongoing R&D and challenges are:

● Materials research, including that for raising the critical temperature

● Mechanical properties of the composite

● Cryogenic cooling and its energy consumption

● Economics – still much too expensive: the currently estimated prices of $1000-3000/(kA m) {with typical critical currents of 20-30 amperes (77K, H=0) and piece lengths greater than 100 meters) should for electrical competitiveness with copper be reduced to 1o $10/(kA-m).

4. **FUSION** (for a brief general review see [89])

The major appeals of nuclear fusion for power generation are: (a) that its fuel is composed of rather abundant elements: deuterium (D) that is plentifully available in ordinary water and tritium (T) that can be easily produced by combining the fusion neutron with the abundant lithium, (b) it has the highest energy density, e.g. the deuterium in a liter of ordinary water would have an energy content of 300 liters of gasoline) (c) the radiation from the process is very low and short-lived (but the environmental problems are not negligible), (d) it is predicted to emit less CO_2 than any other power source, including renewables. The energy density of fusion reactions is 337 TJ/kg for D-T reactions, for comparison, enriched uranium nuclear fission in light water nuclear reactors is at 3.46 TJ/kg, and crude oil at 46 MJ/kg, which is both a big advantage and disadvantage.

The well known and most significant challenges for producing electricity from fusion, that haven't been solved after more than 50 years of research, are the need for the D-T plasma confinement (currently by magnetic or inertial methods) having temperatures of over 100 M°C, and for producing more energy than needed to maintain the fusion reaction, but there are also secondary ones, e..g.

☐ Only about 20% of the fusion energy yield appears in the form of charged particles (the rest neutrons), limiting the energy conversion efficiency.

☐ Lithium resources are less abundant than deuterium resources, and if Lithium batteries end up as those chosen for the huge foreseen market for electric or hybrid cars, the demand will seriously compete with potential Lithium use for fusion reactors. At the same time, research is proceeding to use D-D reactions (that would thus not use Tritium).

☐ Tritium is radioactive and difficult to contain; expected to leak from reactors in some quantity, representing a fairly large environmental release of radioactivity. It's half- life is about 12 years.

☐ The neutron flux expected in a commercial D-T fusion reactor is about 100 times that of current fission power reactors, posing problems for material design. After a single series of D-T tests at JET, the largest fusion reactor yet to use this fuel, the radioactivity required remote handling for a year,

These secondary challenges, however, appear to be much less severe than those using other energy sources.

Fusion has the potential to be a very abundant, and relatively clean and inexpensive source of energy. In fact, if it materializes commercially, it may cause global warming due to straight production of heat due to excessive use of the cheap energy. Past predictions of success and commercialization repeatedly had a 25-year target, and those have increased to about 35 years based on the ambitious multi-national ITER (International Thermonuclear Experimental Reactor) program that is constructing a 500 MW magnetic-confinement fusion test facility in Cadarache, France [90].

The scientific and engineering challenges for developing fusion power for commercial use are formidable but fascinating, and fusion holds important promise for the future.

5. **ENERGY FROM SPACE FOR TERRESTRIAL USE** (cf. [91-95])

5.1 Introduction

In mankind's search for energy in the depth of the earth, on its surface, and above it in its atmosphere and from the sun, and in view of the negative environmental impacts of energy extraction and collection on terrestrial locations, an obvious further extension is the placement of energy collection/generation devices in space with transmissions of the energy for use on earth. The basic concept, with the power generation station placed on the moon, is shown in Fig. 3.

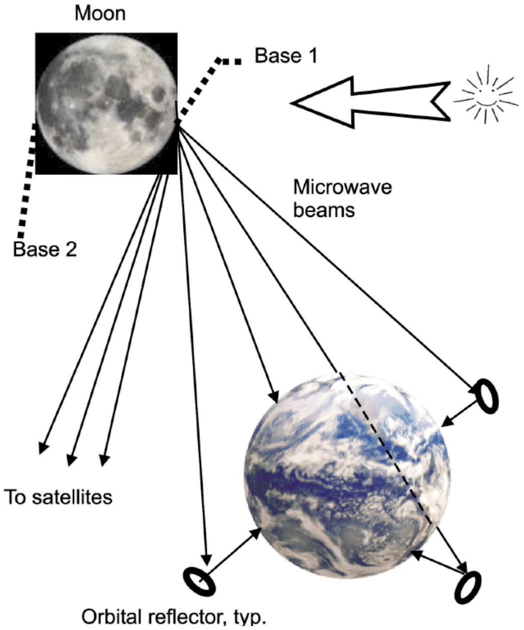

Fig. 3 *Lunar base for generating power for terrestrial use [92].*

Advantages of space based energy devices are:

- Unobstructed by the earth atmosphere with insolation available for nearly 24 hours, and unlimited by terrestrial surface use considerations, it is ideally suited for solar energy use,
- Can thus provide a rather stable base load
- Space is a nearly ideal heat sink for power plants. Being at near absolute zero temperature, it is indeed the lowest attainable temperature heat sink, offering a Carnot efficiency of nearly 100% regardless of the power plant heat source temperature as long as it is higher than that of space.
- Nuclear power generation in space would incur diminished safety and waste disposal difficulties
- Having immense (and ever expanding . . . ?) volume, space would be affected negligibly by any heat addition from the earth.
- It also appears to be a nearly ideal sink for power-generation associated emissions of species which are harmful to earth.
- It doesn't seem that siting of energy plants would be faced with the same difficulties and restrictions that are increasingly becoming a dominant obstacle for their construction on earth.
- In the near-absence of gravitational forces it allows the construction of much lighter (and hence also cheaper) plants: static, wind, and dynamic (such as earthquake) loads are minimal.
- There is every indication that energy plants should last much longer than those on earth, because of the absence of oxidizing agents, rain, dust, hail, and vandalism.
- There are advantages for the distribution of the generated power to terrestrial locations which need it, replacing oil and gas pipelines, tankers, and electrical power lines which are currently limited by resistance losses and land-use consideration.
- Essentially a vacuum, space is a superconductor for electromagnetic-wave/photon energy transmission
- Accidents, such as fire, explosion or implosion, and spread of toxic, carcinogenic and radioactive materials appear to be orders of magnitude less harmful (if at all) to earth and its inhabitants.

There are also significant obstacles, including:

- Cost and energy needed to transport the plant components into space and to construct and maintain it there
- Energy transmission from the space station to earth
- Environmental issues, primarily related to power transmission and to launch vehicle emissions
- Space plant security
- International agreements on space use and energy distribution
- Damage from meteorites, etc.
- Cost, cost, cost . . . The National Strategic Space Office estimates that the cost of space transport to orbit must decline about 50-fold, to $440 per kg for space-based solar power to reach grid parity and become a viable energy alternative [96].

5.2 Location of space power plants

The two primary choices for space power plant location are as satellites in some orbit, or on an existing celestial body such as the moon. *NASA* claimed that the most appealing locations for solar space power plants are in one of several earth orbits, or on the moon, with potential for mining it to provide the material necessary for the power stations. The space power planetary siting advantages are that the plant doesn't need to be maintained in orbit, it is on a steadier platform, and that for example, the moon consists of 30% metals (Fe, Mg, Ti, . . .), 20% Si, 40% oxygen, all directly useful for potential manufacturing the power plants on site. Human presence in this process can be minimized by using highly robotic techniques. It is estimated that moon mining for that purpose can save 30% of the plant cost, as compared with earth-based manufacturing and transportation to the moon. Also shown in Fig. 4, orbiting mirrors can be used for reflecting the microwave beams to earth regardless of moon position. The moon is also a much better launching base for satellites, power or otherwise, especially since the launch energy is about 1/20 of that needed from earth.

5.3 A relatively simple method: orbital solar light reflectors

An interesting approach to using space solar energy is by constructing orbital mirrors of large size, made of reflective thin film mirrors (usually plastic) to reflect the solar natural light onto the Earth during hours that usually experience darkness. This could be used to provide illumination where needed or to extend the diurnal solar power generation as well as agricultural production by making longer period availability of sunlight for crops [97], The basic concept is demonstrated by a simple model, shown in Fig. 4, constructed by the author and his students.

Fig. 4: *Simplified concept demonstration model of a Sun-Earth orbital mirror system showing light on one side of earth (left image) and reflected light on the dark side of earth (right image). Built by the author's students Betsy Rosenblatt, Travis Schlegel and Kamal Shair, 2008.*

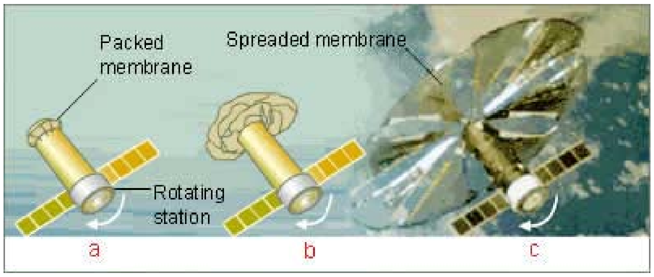

Fig. 5*: Unfurling Process of Znamya 2.5. a: The container with the furled mirror ("membrane") arrives to its orbital location, b: The container is opened and unfurling starts, c: The mirror is unfurled and operational [99].*

The project was done by the Russian Space Regatta Consortium (SRC) [98]. Two experiments were conducted: on February 4, 1993, an SRC-manufactured prototype solar mirror named Znamya 2 was deployed for testing. It was tested at 220 miles above the Earth and was furled inside a cylindrical container, Fig. 5). A 2.5 mile-wide beam of light shone through Europe's skies with the intensity of a full moon [99,100]. Znamya 2.5 was the final follow-up experiment conducted by the SRC on February 4, 1999, using a 25m diameter Mylar mirror to test the improvements made, but the mirror failed to unfold, having been accidently caught up by one of the supply ship's antennae [99]. The U.S. NASA seems not to have conducted similar research, but successfully conducted space experiments on inflatable solar concentrator mirrors made of thin polyimide film substrates coated with a reflective metallic thin film, to focus solar energy onto photovoltaic cells on the same satellite.

While there seems to exist no fundamental technical reason why this concept shouldn't work, several challenges have obviously to be met, the primary are the stability of the mechanical, shape, and radiative properties of the mirrors, their weight (i.e. launch cost), and mechanics of unfurling and erection in space. Preliminary economic analysis by the author and his students shows very encouraging prospects.

5.4 Methods for electrical power generation in space

5.4.1 Solar energy. This energy can be used in a number of ways to produce power: by direct conversion to electricity via photovoltaic (PV) cells, by its conversion to heat for operating some type of thermal power cycle (Brayton, Rankine, Otto, Stirling, etc., [94]), for operating direct thermal-electric energy conversion systems such as thermoelectric generators, or by using its thermal and/or photon attributes for operating and/or catalyzing chemical processes for the production of fuels or of energy storage materials.

Various studies indicate that solar-thermal power generation systems may be produce electricity at lower costs than PV systems, and that they will suffer less performance degradation due to aging and environmental interaction effects.

One of the system concepts is the "Sun Tower" depicted in Fig. 2. It is evolvable and modular, consisting of a ~15 km long common tether made of both electrical and mechanical support cables, which is attached to about thirty 1-MW PV modules, and at its end to a 200-300 m diameter 250 MW FET device phased RF generator-transmitter aimed at a rectenna (receiving antenna which converts the microwave energy to DC electricity) on earth. Each PV module is in the center of a 50 m diameter Fresnel thin film concentrator/reflector. The tower would initially be deployed in lower earth orbit and then moved to its final destination, probably in GEO. A system life > 20 years is sought, and launching at costs lower than $400/kg is expected to be feasible using the 'highly reusable space transportation' systems which are currently under development for other needs. This concept was estimated to represent a factor of 30 reduction compared to the investment required for the original 1970-s reference system.

5.4.2 Nuclear energy. Nuclear fuel has important potential for space power applications, as already evidenced by the use of the energy of radioactive isotopes, and of nuclear reactors for powering existing space vehicles. Its primary advantage is the very high energy content per unit mass, which for fissionable uranium is 6 orders of magnitude higher than that of fossil fuels or hydrogen, and even more so than that for solar energy collection hardware. With current technology, even the entire space reactor system is lighter than a solar PV system producing the same amount of power, noting that reactors for use in space are not designed to be equipped with the same level of protection and containment equipment used in terrestrial nuclear reactors. Space nuclear power systems do not require energy storage. They quite obviously also have a much smaller surface area than solar systems.

Safety in operation of nuclear sources in space is of critical importance. Several techniques have been employed so far. If the satellites are placed in a sufficiently high orbit, it is predicted that the isotope would stay in space, before descending into the atmosphere, for a time long enough to allow the radioactivity to decay to harmless levels. In low orbit satellites the fuel source is to be boosted into a high orbit before the rest of the satellite descends into the atmosphere. Two opposite design philosophies are used for protection during mission aborts and earth re-entry: one is to build a sufficiently strong containment which would retain the fuel upon re-entry, and the other is to allow fuel dispersal, by evaporation in the atmosphere. Both techniques were deployed and it is reported that no substantial radioactive particulates were found in the atmosphere after re-entry. At the same time, it is obvious that further development in this area is required.

5.5 Transmission of the space-generated power to earth

The most commonly considered method for transmitting the electricity collected in space to earth is to convert it in space to microwaves, beam them to a rectenna on earth where it is converted to electricity for distribution. The method was verified experimentally over shorter distances and is predicted to have a space-to-earth transmission energy efficiency of about 80%. A more recent proposal is to convert it in space to laser radiation, which will be beamed to a terrestrial photovoltaic collection station and converted there back to electricity for distribution. With current technology, this transmission method is much less energy efficient than microwaves. In either case the transmission design should be such that it is safe for people and the environment. Studies of microwave transmission have proven feasibility, and predicted safety.

5.6 Space transportation and total cost

The development of space based commercial energy producing systems depends in a major way on the feasibility of launching into orbit the required large amounts of materials, and on the associated costs and environmental impact. The establishment of space power stations that satisfy a reasonable fraction of global electricity need will require thousands of launches per year. This would also require the establishment of hundreds of launch facilities. Larger payloads must be enabled to reduce the required launch rate.

In recent designs, such as the "Sun Tower", the costs are approximately equally divided between the solar array, the launching system, and the transmission system. Analyses indicate that competitive space station electricity prices can be attained if launch costs are reduce to less than $400/kg. At the present cost of $10,000-$20,000, it is clear that launch cost must be reduced by almost two orders of magnitude. The primary effort in that direction is to develop reusable space vehicles, and progress is indeed being made by a number of companies.

5.7. Summary of environmental effects

The primary environmental effects include (1) pollutant emissions and ozone effects of launch vehicles, (2) microwave or laser power transmission, (3) health consequences of ionizing galactic radiation on space workers, (4) pollution collateral with the entire system, such as the production and ultimate disposal of launching devices, solar collectors, PV cells, or nuclear fuel, microwave or laser light generators, radiation-to-electricty conversion systems, including all associated hardware. These environmental effects are controllable, but they require further study, innovation, and possibly larger investments.

An analysis of the life-cycle CO_2 emission intensities of space-based solar power (SSPS) shows that they are 23 gr-CO_2/kWhe, comparable to those of wind and nuclear power [102].

5.8 R&D challenges

Much R&D would be needed to bring space power use to commercial success. 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.

Future generation of power in space for terrestrial use will require massive resources, a long time, and strong and fair international cooperation.

6. REALIZATION OF A FREE AND MORAL ENERGY MARKET

As described in Section 1.5, the price of oil has recently been fluctuating wildly, with a peak to bottom ratio of about 3.6. The peak price is about one to two orders of magnitude higher than the cost of extraction, possibly meaning that financial speculation is overwhelming supply and demand, and all technical improvements. A great concern at this time is that these huge, rapid, and seemingly unregulated price fluctuations seriously threaten the development of renewable energy, and of all energy systems that do not use oil as the fuel for that matter. It is impossible to plan, establish, and maintain an energy business while the price of the conventional business competition can vary in this manner. There is much evidence that speculation, based on uncontrolled human greed, has an important role in creating this serious problem.

Another relatively recent example is the advantage taken by Enron Corporation of poor state and federal regulation of the energy markets, abetted by serious loopholes in the poorly formulated California Deregulation Plan (cf. [102]) to defraud its customers and shareholders. The actions not only bankrupted the corporation and lost billions of dollars to its shareholders, but also caused serious damage to a deregulation plan that was intended to encourage competition among utilities and thus to lower the price for consumers.

It is a sad observation for scientists, engineers and for everyone who believes in the vital need for sustainable development that all their efforts to meet the energy predicament can be easily set back due to immoral greed and lack of regulation. While governments' role in subsidizing certain energy systems is not always useful, they are best suited to enact and enforce wise legislation and promote education, which encourage economic integrity of the energy field.

7. SOME RECENT ENERGY R&D BUDGETS AND TRENDS

7.1 The United States

2009 is an important year for energy in the U.S. because the voters turned the 8-year leadership by a Republican party government and president into the Democrat party hands, alongside with the historically significant election of President Barack Obama. The new administration, following basically its campaign promises but also faced with the immediate worst economic downturn since the great depression, started making significant changes in many directions, including in the energy and environment areas. In this section I briefly summarize the U.S. Department of Energy (DOE) fiscal year 2010 budget request that pertains to the energy and environment area [103,104] and discuss changes relative to past years under the previous administration. Some of the statements are taken verbatim from the DOE budget documents, but the commentary is entirely the author's and does not represent, nor is sanctioned by, government.

The requested budget is stated to support the President's commitment to the challenges of economic uncertainty, U.S. dependence on oil, and the threat of a changing climate (reducing U.S. carbon emissions) by transforming the way the US produces and consumes energy. Most impressively in purpose and magnitude, an additional one-time allocation of $38.7 billion from the American Recovery and Reinvestment Act of 2009, is to be added to the 2010 year DOE budget and used (typically starting this year with a duration of about 3 years) to accelerate investments in energy conservation and renewable energy sources ($16.8 billion), environmental management ($6 billion), loan guarantees for renewable energy and electric power transmission projects ($6 billion), grid modernization ($4.5 billion), carbon capture and sequestration ($3.4 billion), basic science research ($1.6 billion), and the establishment of the Advanced Research Projects Agency ($0.4 billion), all "to help jumpstart the economy and save and create jobs at the same time". To characterize the enormity of this expenditure, the $38.7 billion from the American Recovery and Reinvestment Act is more than 6-fold higher than the DOE annual energy R&D and Science budget and about 16-fold higher than the annual amount that the EU 7th platform allocated for R&D in roughly the same areas.

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

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

The remaining information presented here about the budgets must be prefaced with a statement that examination of governmental and institutional aims and budgets is very difficult, in part because of duplication and overlap of programs, and frequent changes across them, and all the numbers given here are thus not always precise.

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

In more detail, some of the most important budget changes include:

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

- 21% decrease (compared with the 23% increase in 2009) in the *Fossil Energy* program to \$882 million, includes \$404 million for clean coal technology, and \$25 million for gas hydrates ("ultra-deepwater natural gas"). Very noteworthy is that here the Recovery Act is to provide \$3.4 billion additionally for carbon capture and storage (CCS) and for the Clean Coal Power Initiative (CCPI), and more than offsets the \$229 million decrease in the DOE's annual Fossil Energy budget.
- Investment tax credits (typ. 30%) of \$3.15 billion was allocated in 2005 and 2008 for accelerating commercial deployment of technologies central to carbon capture and storage, plus an additional \$2.3 billion allocated this year from the American Recovery and Reinvestment Act of 2009 for manufacturing facilities that produce specified advanced energy products such as renewable energy power systems, automotive storage systems, energy conservation, carbon dioxide capture and storage (CCS) technologies and other systems designed to reduce greenhouse gas emissions.
- A 4% reduction in the fission nuclear energy program, to \$761 million, aggravated by the fact that its R&D portion is reduced by 22%. The program continues to be aimed to develop advanced nuclear power for meeting energy and climate goals, to develop advanced, proliferation-resistant nuclear fuel cycle technologies and to maintain the national nuclear technology infrastructure. The highlights are:
  - Work will continue on nuclear waste storage and disposal options, and "Generation IV (Gen IV)" advanced nuclear reactors, including the sodium-cooled fast reactor, molten salt reactor, supercritical-water-cooled reactor, lead-cooled fast reactor, very high temperature reactor, and the gas-cooled fast reactor (this is also the recommendation of the Generation IV International Forum [52])
  - All funding for development of the Yucca Mountain facility for permanent geologic storage site for spent nuclear fuel and high-level radioactive waste nuclear waste has been eliminated. The Administration intends to evaluate alternative approaches for meeting the federal responsibility to manage and ultimately dispose of spent nuclear fuel and high-level radioactive waste from both commercial and defense activities. This is a remarkable reversal of past year's decision to invest an additional \$495 million for that facility (after spending about \$13.5 billion (2007 value) over the past 26 years), touted all along as the main U.S. solution to its nuclear waste disposal.
- \$4.6% increase (to \$421 million) in the fusion program, including continuation of the contribution to the multi-national ITER program;
- A 52% increase (to \$208 million) in the electricity delivery and energy reliability program. A long overdue attention to this historically underfunded but critical program, that addresses clean energy transmission and reliability, smart grid R&D, energy storage, cyber security of the electric distribution system, permitting, siting, and analysis (that uses education, outreach, and analysis to help states, regional electric grid operators, and federal agencies develop and improve electricity policies, market mechanisms, state laws, and programs to assist in modernizing the electric grid and the development of new electric infrastructure needed to bring clean energy projects to market), and infrastructure security and energy restoration.

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.

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

7.2 The European Union (EU)

The EU (that is the largest importer and second largest consumer of energy in the world) 7th Framework Programme (2007-2013) had a 50% increase in the energy area (energy, environment, transportation) over the 6th program, and is annually about \$1.68 billion plus \$0.77 billion for the nuclear research in Euratom for a total of \$2.45 billion/year (at 1 Euro = 1.40 US\$) [105]. Some of the goals for the year 2020 include a 20% reduction of energy use, a 20% share to renewables, and all new coal power plants being of the CCS type. To accomplish this, he EU Commission presented in 2007 a strategic plan to accelerate the development and deployment of cost-effective low carbon technologies for "fight against climate change, security of energy supply and competitiveness of European companies" with a funding of €3 billion per year [106]. In 2009 they requested €50 billion over the next 10 years, thus tripling the annual allocation. It is noteworthy that individual European countries also have their own energy R&D budgets that in total exceed that of the EU.

7.3 Japan

Japan's energy R&D program was \$3.6 billion in 2006 and called for an increase via the "Cool Earth Promotion Programme" of \$30 billion in energy and environmental R&D funding over the next five years. 62% of the 2006 budget have been spent on nuclear research, followed by energy conservation and efficiency at 12%, fossil fuels at 9%, renewables at 7%, and power and storage technologies at 3%. It is noteworthy that Japan spent in 2006 roughly 0.083% of its GDP on energy R&D, more than double the proportion of GDP spent by the second highest nation in the category, Finland, about triple that of the United States, and 17-fold that of the EU 6th Framework budget in the same year [107].

In its report on energy in Japan, the IEA recommended "the development of a more integrated, comprehensive and transparent energy R&D policy framework by explicitly linking national energy policy goals with energy R&D priorities through a transparent and long-term strategic research funding roadmap, ensuring that funding is allocated according to a formalised and streamlined process, developing a standard and transparent protocol where funding for and tendering of research proposals are linked to the R&D priorities". Such a recommendation, I note, is valid for most countries' energy R&D policies and plans.

8. A summary of possibly sustainable paths to the future

- Conservation, as long as it meets the sustainability objectives
    - Higher efficiency with controlled rebound
    - Substitution for lower energy intensity products and processes
    - Recycling
    - More modest lifestyle
- Renewable Energy
    - Highest growth rate:
        - Solar, mostly PV
        - Wind
    - High potential:
        - Some biomass
        - Hydro, especially small
        - Geothermal
- More efficient and cleaner use of fossil fuels (for this century); "Clean coal"; reliable and economical CO_2 sequestration
- More efficient transport, with attention to its management
- Enabling energy saving in the building sector by empowering free market forces
- Nuclear energy if breakthroughs in fusion or in element transmutation, and/or when Gen IV reactors are commercialized
- Significantly improved energy distribution grids
- Much better energy storage and its significantly expanded use
- Superconductivity, in longer term
- Space power generation for terrestrial use?
- All energy development must be performed sustainably
    - This requires the further development and application of sustainability science.
    - Sustainable development requires close cooperation between all humans, across any borders they drew, vision of the future, and much respect for the environment that we so temporarily occupy.
    - It is not conceivable that sustainable development can take place without applying reasonable measures for population control.

The critical problems that energy development poses and the possible paths to the future create at the same time great opportunities for respected solutions by the engineering/scientific community that promote new and expanded creativity, higher employment, and higher job satisfaction. It also offers special prospects for small enterprises and nations that are not hampered by the inertia inherent in larger organizations.

A political system is needed to support rapid and effective movement along the new paths, and to plan beyond its tenure, and that often prefers solutions that are primarily supportive of its own survival: popular support for sensible paths should be sought/educated to diminish this obstacle

Many of the innovative solutions require very long periods of time. It is of vital importance to start intensively now, so we wouldn't be too late.

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