Chemical Challenges in Renewable Energy

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This purpose of this talk to is evaluate the issues related to renewable energy, and specifically challenges for the chemical sciences in renewable energy technology. The numerical data presented in this talk are all taken from peer-reviewed sources, primarily the World Energy Assessment (www.undp.org/seed/eap/activities/wea). I have also had valuable input from many people during the preparation of this presentation. However, the conclusions and opinions expressed in the viewgraphs and the accompanying text are my own except where specifically indicated.

I will mostly focus on energy supply, as opposed to demand issues, although of course supply and demand cannot be fully separated. To evaluate the role of renewables, we must first lay the groundwork for whether there will be a significant role for renewables in the context of the overall global primary power supply. The outline of the talk is therefore to discuss where we get our current power now, in particular our primary power sources, and what their costs are currently relative to power obtained from renewable resources. We will then discuss the availability of the supply of fossil fuels based on the estimated available global reserves and resource base, and will then calculate the estimated length of supply, regardless of cost, of these fuels based on our current global fossil energy consumption rate. These data will provide a context for the future and will also set the scale of the issues involved with energy supply. Then we will estimate the future global energy demand, and see how for how long this demand can be fulfilled solely by consuming fossil energy resources. Then we will consider what future constraints might be imposed by sustainability issues, which I believe arguably are the most important potential game-changing variable with the respect to perturbing the current mix of primary power that we might foresee looking out 20-50 years. This discussion will set the scale for the need for carbon-free power that would be provided by utilization of renewable energy resources. We will then discuss the theoretical and practical potential of the various renewables, and will evaluate which renewable resources could meet the scale set by the problem that is posed here. Then, we will focus on challenges, not only to the chemical sciences, but for both technology and policy issues related to the global demand and supply of energy in the next 50 years.

The data in this talk are mostly taken from the World Energy Assessment, although they are in concurrence with the data contained in the recent U.S. National Energy Policy report where the reports overlap. The data are not all for the year 2000, but they are close in date and are therefore reasonably comparable. Although there are a range of issues both politically and regionally regarding security of supply vs global supply, the focus of this talk will be to remove these variables and consider solely the global energy supply and demand issues.

The second slide summarizes the sources that comprise current global energy production. I have done a unit conversion throughout and have converted quads of oil and cubic feet of gas and kilowatt hours of electricity into a common unit, mean burn rates of energy in terms of watts. So, for example, I have taken the total energy content in joules of oil consumed globally in a year, divided by the number of seconds in a year, and obtained a mean average burn rate for oil. That number is in watts, and in fact, is in terawatts (1 TW=10^{12} W). A similar unit conversion has been done for all of the other energy sources, to put all of the quantities in this talk onto a common scale.

About one hundred quads of energy from all sources was consumed in the U.S. in 1998, which is a 3.3 TW mean burn rate. The mean globally energy consumption rate was 13 TW in the year 2000, and of course, the U.S. consumed about a quarter of that amount. Another important point is that high value energy, electricity, is a significant, but on the order of 10% globally, 15% approximately U.S., of the total energy consumption. Of course, electricity is not primary power. The fossil fuel sources of primary power--oil, coal, and natural gas-- make up the lion's share of where we get our energy. Hydroelectric power produced 0.286 TW in 1998 as the largest renewable power source. The 1.21 TW of biomass is not in the renewable column because it represents unsustainably burned biomass, as opposed to energy farms. Other renewable energy, including renewable biomass, provided only 0.286 TW of consumed power in 1998. Nuclear fission plants generated 0.828 TW of power in 1998 (of which approximately 30% was converted into electricity). This sums up our current primary energy supplies.

The next slide summarizes the various sources of the renewable energy component of the overall energy mix. A logarithmic scale is required to put these various contributions into relative context. The total sustainable biomass mean power produced, broken down into both electrical power, heat, and ethanol, only comprised a total of 10^{-1} TW watts out of the 12-13 terawatts of total primary power produced globally in 1998. This biomass is the sustainably burned portion of biomass, such as energy farms in Brazil. Wind produced 2×10^{-3} TW of power in 1998. Solar electric power production is growing rapidly, but off of a very small base, providing in 1998 a part in a million of the total global primary power. Solar thermal and other renewable resources are also currently small fractions of the overall primary energy supply.

But what about the cost? The next graph summarizes as of 1997 the estimated fully amortized costs for electricity production from various primary energy sources. The cost figures are certainly good to within a factor of two in the context that is needed for this presentation. A coal-fired power plant is currently the least expensive way to produce electricity, followed closely by nuclear fission, although there is some debate about whether one ought to include the insurance and other associated costs with the nuclear power figure quoted here. Next in cost is electricity from gas, followed by electricity from oil. Of cousre, incremental capacity costs are different for marginal capacity costs and the former currently favor gas for new electricity-generating power plants. Then more expensive is electricity from renewables. Wind in favorable sites can be perhaps 4 cents per kilowatt hour or even less, and currently solar photovoltaic electricity is 22 cents per kilowatt hour, or greater, depending on siting and other variables.

But these oft-quoted figures are not the whole story of why renewable energy does not comprise a greater fraction of the current total energy production. An important goal is not only to get solar and wind-generated energy competitive with electricity production from fossil energy, but to get renewable energy in general competitive with fossil energy. Remember that electricity is high value energy. This can be seen by evaluating the cost per joule of energy, as shown in the next slide (with the costs expressed as $/gigajoule). Clearly, coal is the cheapest, then oil, and then biomass, and then 5 cents per kW-hr of electricity is yet another factor of 5 higher in terms of cost per joule of energy content, relative to fossil energy. Hence to be competitive economically in the total energy picture, as opposed to the portion of secondary energy that is consumed as electricity, the cost of energy from renewables has to decrease by factor of 25-30, as opposed to a factor of 4-5.

So perhaps the price of fossil energy will naturally rise due to supply/demand economic forces as we exhaust the supply of these fossil fuels. To evaluate that possibility, we need to consider the total amount of fossil fuel resources and reserves that are available and then divide that value by our current burn rate of these energy sources. This approach is different than Hubbert curves that projected the production peaking of U.S. domestic oil in the latter 20th century, in that various factors affect domestic production alone, including geopolitical forces and other drivers that are not always transparent to analyze. We instead will discuss a purely geological estimate of the global quantity of fossil energy and then compute, at the current burn rate, how long this available supply will last.

We need to consider both the estimated total reserves (i.e. quantities of fossil energy with 90% confidence that such supplies exist), from both conventional and unconventional sources, and the estimated resource base of the various fossil fuels: oil, gas, and coal. From simple arithmetic of dividing the total reserve and/or resource base by the current burn rate of each type of fossil energy, it can be seen that we have between 40 and 80 years worth of oil reserves globally at our current burn rate of oil, and we have between 50-150 years of oil if the resource base is included. We have between 200-500 years of reserves of natural gas, and between 207-590 years of gas reserves, not including the natural gas potentially available as methane clathrates in the continental shelves. Similarly, we have between 200-2000 years of coal.

The conclusions of this calculation are that we have an abundant, relatively inexpensive global resource base of fossil fuels. There are, of course, different geopolitical and regional factors that are certainly going to come into play (and which have historically done so) that will affect pricing of energy, but globally, we have an abundant inexpensive resource base of fossil fuels that will last us for hundreds of years, if we choose to exploit it. Furthermore, at some additional cost, one type of fossil fuel can be convereted into another, so that a limited global supply of one fossil energy resource (for example, oil) could be compensated for in principle by additional consumption of another fossil fuel (for example, coal). And so one can conclude that renewables will not play a large role in primary power generation unless or until some technological breakthrough is achieved, or unless/until some unpriced externality becomes introduced into energy pricing. This is a controversial conclusion to some audiences, but I believe that the numbers presented herein support the conclusion analytically.

So, where might that externality appear, and are there any "game-changers" to consider related to energy? There are about 100 papers on sustainability, but I will summarize just one by Hoffert et al.. I have discussed the conclusions fairly extensively with Seth Potter and Marty Hoffert, two of the authors. The data presented therein are in turn recast from data contained in the 1992 report of the Intergovernmental Panel on Climate Change. This IPCC report has been updated recently, but the most recent values are still in reasonable accord with the general conclusions presented in this talk.

The first graph on the next slide presents the projections for global population vs time into the 21st century. Population growth is of course is the key driver for energy demand, involving the number of people on the planet that have to be sustained. The population estimate in 2050 is for about 10 billion people; the year 2050 is the representative out date that we will subsequently discuss here. The global population is now approximately 6 billion people, and the data are shown on a logarithmic scale, so population growth dominates energy demand in fact.

Next, it is useful to break down energy consumption per capita globally into two factors, one which reflects GDP (gross domestic product) growth, and the other which represents energy consumption per unit of GPD. The mean value of global GDP has been increasing historically at about 1.6% per year. One can debate whether or not a sustainable GDP growth rate is 2% or 1.4%, but 1.6% is a number that most would consider to be reasonable. Since energy is needed to support GDP growth, the energy consumption per unit of GDP also needs to be considered. The global energy consumption per unit of GDP has historically been going down, and in fact it has been going down globally historically at approximately 1% per year. The U.S. energy consumption per unit of GDP is declining somewhat more rapidly, at approximately 2% per year. In fact, the commitment from the current U.S. administration is to maintain that rate of decline of 2% per year. However, because the industrialized countries are not meeting the same rate of decline as the developing countries, the global average rate is a decline of about 1% per year in energy consumption per unit of GDP.

This separation of demand into the above three factors is useful for another reason. Specifically, it already builds energy efficiency into the demand side of the equation. So factors related to changes in the energy mix to more energy efficient fuels, use of fuel cells, and conservation efforts are already built in to the 1% global decline in energy consumption per unit of GDP. This breakdown conveniently allows us to focus on the supply side of the problem for the remainder of this talk.

Combining the three graphed quantities allows computation of the energy demand vs year for the period of interest. Even if energy consumption per unit of GPD were increased to a level so as to balance per capita GDP growth, which is highly doubtful because it would imply sustained economic growth at constant total energy consumption per capita, the projected rate of growth of global energy demand is still dominated by rate of population growth.

The calculated energy demand is summarized in the next graph. Focus only on the top curve, which plots the total energy demand vs year. The projection is for 28 TW in 2050 for global energy demand. Of course the demand increases if one projects out further. The IPCC did this projection as well, and this curve is the result of the IPCC's "business as usual" scenario, labeled IS92a.

The next issue to consider is what is the mix of energy going to be like to meet that primary power demand in support of that number of people. To estimate that mix, we need one more item. We need to look at the carbon intensity of the energy mix. Historically, the mean carbon intensity (kg of C emitted to the atmosphere as CO_2 per year per W of power produced from the fuel) of the global energy mix has been declining. As we have evolved into an industrialized society, we have gone away from wood unsustainably burned, which has the largest carbon emissions per joule produced from the source. And then coal, since it has almost no hydrogen it, is second in carbon intensity, and then oil, and then natural gas. The IPCC projected, I believe optimistically, that we will continue along the historical trend of mean carbon intensity all the way through to 2050, in terms of going toward a mix favoring the cleaner burning fuels from a carbon emissions viewpoint. If we were to do that, the projected carbon intensity is $\approx$ 0.45 kg of C yr^{-1} W^{-1}, which is lower than that of any of the fossil fuels. The only way one can reach this value of mean carbon intensity is through a significant contribution of carbon-free power to the total energy mix. In other words, to obtain a mean carbon intensity below that of an economy entirely based on natural gas requires significant power produced by carbon-free sources. Furthermore, to the extent that the mix of fossil fuels used to generate power is not 100% natural gas, but is roughly also equal parts oil and coal, even more carbon-free power is required to maintain the mean average of the total mix at the 0.45 value.

Now why is this important? Clearly, the calculation above shows that we have sufficient global fossil fuel resources to meet even this demand requirement in 2050 and beyond. And the discussion above also shows that fossil energy is likely to be a relatively inexpensive method of obtaining primary power even in 2050 and beyond, given its adequate supply globally in the various forms of oil, gas, and coal. The reason for considering the carbon intensity is that even though we could in principle burn fossil fuels to meet this demand, we might not wish to do so, due to other (primarily environmentally related) consequences.

The exact breakdown of how much carbon-free power is needed in 2050 to meet the target mean carbon intensity value depends significantly on the fossil energy mix used by India and China, which play heavily into projections due to their large populations and their increasing use of energy per capita as they undergo sustained economic development. Nevertheless, projecting roughly equal consumption of coal, oil, and natural gas in terms of the energy mix, one can then calculate how much carbon free power is needed in order to obtain the target mean carbon intensity value in 2050. This is important because it enables prediction of the carbon emissions that will be produced as a consequence of burning that amount of fossil fuels.

The next graph shows the same total energy demand plot that was presented earlier, rising to 28 TW by 2050. It also shows what is needed in terms of the energy mix to sustain certain atmospheric CO_2 concentrations. For example, the line labeled WRE 750 is a line showing the limit on fossil energy consumption at the quoted mean global carbon intensity value that would be needed to produce a 750 ppm atmospheric CO_2 level, triple the pre-industrial atmospheric CO_2 concentration, in 2050. The line labeled WRE 550 is for 550 ppm of atmospheric CO_2, the upper limit of what most climate change researchers, although there are clearly major uncertainties, would say is the upper limit that would lead to about a 1-2 ºC mean global climate temperature rise. The latter temperature rise would have significant but possibly not catastrophic impacts on the earth’s climate. For example, the coral reefs would probably all die by this point. But, we would be able to adapt, at some level, as humans to such a change; although at 750 ppm or higher of atmospheric CO_2, most people in the modeling effort feel that the impact globally would be quite serious.

The point here is that the level would be even above 750 ppm of atmospheric CO_2 if we met all the demand with that optimistic mix of carbon intensity. The “business as usual” scenario, with its optimistic projection of the carbon intensity, in fact produces CO_2 levels higher than 750 ppm by 2050. To the extent that the target carbon intensity value is not reached, if demand is fulfilled through fossil energy consumption, the atmospheric CO_2 levels would climb even higher. To lower the carbon intensity further, one could lower the consumption of fossil fuels and make up the remainder from carbon-free sources. That would, for example, require more carbon-free power to stabilize the atmospheric CO_2 levels at 550 ppm. Because the CO_2 emissions are cumulative in the atmosphere, to stabilize at 350 ppm of atmospheric CO_2 would require utilization of essentially no carbon power by 2050, instead getting the full 28 TW of demand solely from carbon-free sources.

The next graph presents a concise summary of this issue. It presents the amount of carbon free power needed to reach certain atmospheric CO_2 levels as a function of year. Recall that 13 TW was the global primary power production, from all sources, in the year 2000. By 2050, to merely stay on the IPCC "business as usual" scenario, with the atmospheric CO_2 levels rising above 750 ppm by 2050, will require 10 TW of carbon-free power. To stabilize at 550 ppm of CO_2 would require ≈20 TW of carbon-free power. **In other words, the projection is that we will need as much as twice as much carbon-free power by 2050 than the total power produced, from all sources globally, at present**.

So what did Hoffert et al. conclude? They concluded that these projections underscore the pitfalls of "wait and see". We have no price signals now, we have socioeconomic inertia, and we have no idea how we will get the needed technologies developed soon enough so that they could be capitalized on the needed scale to actually be deployed by 2050. Hoffert et al. called for a Manhattan Project, or an Apollo Space Program effort to develop the needed carbon-free energy technology in a sufficiently timely fashion, so that we could implement it on this scale when it is needed.

What we certainly can say from my viewpoint is that *if* we need such large amounts of carbon free power, then current pricing is not the driver for energy supply in 2050. At the least, the prudent approach is to be comfortable that the level of investment in R&D being devoted to carbon-free power technologies that could possibly meet the anticipated demand requirements is commensurate with the risk we are willing to take that this "game-changing" scenario imposed by an unpriced externality will turn into reality.

Now that we have set the scale of the issue at hand, in the remainder of this talk we will consider what sources, almost independent of cost, have the potential to provide such large amounts of carbon-free energy.

One option that is not on the charts in this presentation, but which must be included prominently in any discussion of carbon-free power, is nuclear power, either from fission or possibly in the future from fusion. Currently about 400 nuclear power plants exist globally. The IPCC projections included an expansion of nuclear power in arriving at the quoted energy mix overall. However, it is possible to consider a much larger contribution of nuclear power to address the carbon-free power need. Nuclear power plants typically do not scale well because of heat dissipation, and their size is now about 1 GW. To produce 10 TW of power would require construction of 10,000 new nuclear power plants over the next 50 years, i.e., one every other day somewhere in the world for the next 50 years. I will leave the reader to decide whether or not that is a viable option, but it is technically possible in principle as an approach to obtain the required level of carbon-free power.

Another approach would involve use of fossil fuels in conjunction with carbon sequestration. In this approach, primary energy would still primarily be obtained from fossil fuels, except that the fossil fuels would be converted at a select number of central locations into a non-carbon-containing fuel, presumably H_2. The conversion is necessary at a limited number of central locations because it will otherwise be prohibitively difficult and expensive to recollect the emitted CO_2 from distributed sources, concentrate it, and then sequester it. The CO_2 emitted at the central locations would presumably then be sequestered either in the deep ocean, in geological reservoirs, or perhaps through conversion to carbonates. The questions of concern with sequestration involve whether it can work technically on the needed scales of 10-20 TW per year for an extended period of time. Burial of gigatons/year of CO_2 in the deep ocean will eventually change the pH of the ocean (estimates are that the local pH change will be about 0.1 pH units on a decade timescale) and thereby induce potentially radical ecological change in the biosphere. Sequestration in geological reservoirs is potentially promising, provided that the reservoirs will remain intact. For example, apparently at present approximately over 1 million holes exist from drilling operations in Texas alone. The collective leak rates of the reservoirs must be significantly lower than 1% sustained over a century-millenia-type time scale, because otherwise after 50 years of sequestration the yearly emissions from the reservoirs will be comparable to the emission levels that one was attempting to mitigate in the first place. A significant fraction of existing fossil-derived power plants could be retrofitted to allow for sequestration if it worked on the needed scale; however an equally significant fraction are too remote from the location of suitable geologic reservoirs and either the CO_2 would have to be pumped long distances or entirely new plants would have to be suitably sited and constructed. In addition, significant additional costs will be incurred in converting the entire energy distribution system to either electricity or the required non-carbon-containing fuel, presumably H_2. Sequestration should definitely be explored as an option but it is far from clear that it will technically work at scale or what its actual overall energy system cost will be.

Let me turn then to the various possible renewable carbon-free energy sources. Renewable resources are conveniently categorized into hydroelectric, geothermal, wind, biomass, and solar.

We will first consider hydroelectric power. In some sense hydroelectricity is a model renewable energy resource: it is relatively inexpensive, benign, and available in many areas of the world. However, the total hydrological energy potential of the planet, including the energy involved the water flow of every river, lake, stream, amounts to approximately 4.6 TW. Of course, one can not practically extract all of that power potential because one can't dam up a small creek bed and get anything useful out of it, and for example, one can't dam up the Hudson River, even if one could get hydroelectric power out of that in principle. The amount of technically feasible hydroelectric power globally has been estimated to be about 1.5 TW. Since hydroelectricity is relatively economical currently, it has already been exploited to a large degree in locations where it is favorable to do so. In fact, the global installed capacity in 1997 was 0.6 terawatts, and since hydro plants run on average at 50% of capacity, 0.3 TW of power was produced globally from hydroelectric resources in 1997. Clearly, one cannot significantly approach the requirement for 10-20 TW of carbon-free power primarily through the exploitation of hydroelectricity. Hydroelectricity is a very attractive renewable resource that should be continued to be exploited wherever possible, but it is not going to make a significant impact towards meeting the 10-20 TW global carbon-free power requirement in the mid 21st century.

Let's next consider the energy potential and constraints associated with use of wind as a renewable resource. The map presented is from the NREL web site; one can also find a somewhat updated map about wind energy there as well. If one sites windmills at 5% spacing, which is about the optimal spacing of windmills so that they do not obscure each other, and if one covered no excluded, environmentally sensitive lands or urban areas, one could produce a significant amount of electricity. For example, if windmills were deployed in all the favorable siting places in North Dakota, 36% of the U.S. domestic electricity production in the year 1990 could be generated. Texas has some favorable sites, as does Oklahoma. But how much power is this actually? The total electricity consumption in 1990 was roughly 0.4 terawatts. So this amount is small compared to the 3 TW that is currently produced domestically from all of energy sources.

It is similarly useful to expand the discussion of wind to a global scale. Globally, 27% of the earth's land surface is rated as class three with respect to wind electric potential. A class four rating represents land having a mean wind speed at a certain height above the ground at which the windmills are roughly economical now at about 3-5 cents per kilowatt-hour of electricity production. Use of class three rated land projects potential advances in wind turbine technology that possibly might make such lower wind velocity areas economical in the next 50 years. Adding up all of that area over the entire globe, and considering practical siting constraints, produces a total electrical power potential of about 2 TW for terrestrial wind power.

The offshore electrical power potential of wind is larger than 2 TW and, in some cases, such installations makes sense geopolitically. In Europe, for example, wind farms are located close offshore. However, realization of a demand requirement of 10-20 TW of carbon-free power primarily through wind-generated electricity would involve large windmill installations far offshore. Then the issue of transmission losses come into play, as to how does one get the power generated offshore to the land-based regions where it is needed to meet demand. In addition, it is not clear what the impact would be on the regional weather if for example, 50% of the energy in the atmosphere were removed in North Dakota through an exhaustive installation of windmills as would be necessary to produce the 0.4 TW of domestic electricity from the available class 4 wind resource areas.

Exploitation of wind-generated electricity on a large scale is challenging in the U.S. for another set of important reasons. The map of North Dakota brings out an important point, which is that the wind resource is not located where the power demand is, as not a large fraction of the U.S. population is located in North Dakota. The grid cannot handle that much power if we tried to put such into it. Furthermore, wind is a relatively mature technology, but it is an intermittent source, and demands an accompanying energy storage system. Probably the best way from an engineering point of view to provide the storage capacity and thereby convert an intermittent resource into baseload power is thought to involve the use compressed air storage in the windfarm. The penalty of including storage is about 1 cent per kilowatt hour, so such an approach becomes interesting when wind-generated electricity is about a factor of two lower in cost than it is now. But that calculation applies for electricity, not for primary total power, which requires much greater cost reductions to have wind energy be competitive.

The next renewable resource to be discussed is biomass. Biomass is very inefficient because plants using photosynthesis only store <1% of the total incident energy that they receive from sunlight, under optimal growing conditions at peak times of day. Hence, the total amount of land needed to produce 20 TW from biomass, knowing that currently production of 3 TW of power would require 600 million hectares of land, would require 31% of the total land area on earth covered by energy farms devoted solely to producing biomass to meet the carbon-free energy demand requirement.

The next slide shows the same calculation from a “bottom-up” approach. The total land with crop production potential on earth in 1990 was $2.45\text{x}10^{13}$ m^2, of which 0.897 m^2 was cultivated. The additional land estimated to be required to support 9 billion people in 2050 is $0.416\text{x}10^{13}$ m^2 (due to expected increases in agricultural efficiency); hence the remaining land available for biomass energy production is $1.28\text{x}10^{13}$ m^2. Experience shows that biomass crops under very favorable circumstances can produce 8.5 oven dry tonnes/hectare/year. At 20 GJ higher heating value per dry tonne, if the entire area of $1.28\text{x}10^{13}$ m^2 (10% of the total land on earth; all of the cultivatable land not required for food) were functioning as an energy farm at this power production level, would produce 7-12 TW of power. The higher value of 12 TW was obtained assuming a doubling of the biomass energy yield/hectare to 15 oven dry tonnes/hectare/year, as has been reached in some demonstration-scale projects in certain areas, although many feel that the 8.5 oven dry tonne/hectare/year is optimistic for a global average as well. However, it is very possible and in fact likely that there are not sufficient fresh water resources to perform farming on this large a scale. Furthermore, the above calculation assumes that the net energy return from such biomass farms is equal to its gross energy production, with minimal energy inputs required to fertilize and maintain the farm, collect the biomass, and burn it in a central location. Challenges to energy science then arise as to how can one very efficiently convert cellulose to ethanol, and is it possible to develop ethanol fuel cells for example that could utilize this fuel efficiently? Even with these favorable assumptions, it is clear that biomass could be a significant contributor to the overall 10-20 TW of carbon free power requirements, but can not alone be relied upon to meet this demand requirement.

The last renewable resource to consider is solar energy. The solar constant is $1.76\text{x}10^5$ TW, hence, there is ample solar energy potential. **Solar energy is, in fact, the *only* renewable resource that has enough terrestrial energy potential to satisfy a 10-20 TW carbon-free supply constraint in 2050.** From the $1.2\text{x}10^5$ TW of solar energy that strikes the earth's surface, a practical siting-constrained terrestrial global solar power potential value is about 600 TW. The numbers range from very conservative estimates of 50 TW to optimistic estimates of 1500 TW, depending on the land fraction devoted to power generation. A good number to use for onshore power generation potential is probably 600 TW. Thus, for a 10% efficient solar farm, at least 60 TW of power could be supplied from terrestrial solar energy resources. For calibration, photosynthesis currently supplies 90 TW globally to make the biosphere run, so the amount of power available from the sun is very large number by any measure.

Before investigating "active" energy production from solar energy in more detail, let's consider issues related to solar-derived space heating. If a significant amount of land is going to be covered with materials that absorb sunlight to generate fuel and electricity, then a question naturally arises as to why doesn't one exploit primarily the waste heat from these solar energy farms to provide heat and power for domestic and industrial uses. The reason is that there is a large mismatch between supply and demand for the waste heat, because the heat is not needed to heat homes when the sun is out; the heat is needed in winter, not summer, etc. The accompanying entropic mismatch between supply and demand requires storage of the heat, and storage of low grade energy (i.e., heat) is very inefficient and expensive. Furthermore, the world market for space heating is 1.6 TW. This value will grow somewhat with increases in population, but most energy is not used for space heating. Energy use is now roughly equally distributed between four sectors: transportation, residential/commercial, industrial, and transforming energy from one source to another. So, even if the whole world market of space heating were supplied from solar resources, one would not reach the 10-20 TW level, nor would it be inexpensive to do so because of the supply/demand mismatch issues. High temperature solar thermal is currently the lowest cost solar thermal electric source, and this technology has the potential to provide electricity that is competitive in price with that generated from fossil energy in the long term. However, it needs large areas in the sunbelt to work, and so has a limited global energy potential on the 10-20 TW scale that is being considered in the context of carbon-free power production in 2050.

Let's then return to the evaluation of solar energy as a resource for energy production. The actual land area that is required to produce 20 TW of carbon-free power from solar energy is readily calculated. It is 0.16% of the earth's surface, or $5x10^{11}$ m^2.

The next slide shows this graphically, displaying two boxes, one showing the land area required to generate 3 TW of power, the other showing the land area required to generate 20 TW of power, assuming an overall 10% conversion efficiency of the amount of solar energy that is incident on the land (day/night, seasonal, and latitude averaged).

Another view of this is from a global standpoint. The next slide illustrates six 3 TW boxes. One would not do it this way at all, of course, instead distributing the sites much more widely. Nevertheless, it is just interesting to see the scale of the problem in land area that is being discussed.

Another measurement approach is to consider the total U.S. land area and the mean insolation per unit of this area. Producing 3 TW at 10% efficiency would require covering 1.7% of the land in the U.S. The size of even this project (comparable to the land devoted to the nation's interstate highways) should not be underestimated. For example, if one put a 10% efficient solar energy conversion unit on every home rooftop in the entire U.S., one would generate only 0.25 TW of power. So, the 10-20 TW can not be requirement by covering everyone's house with solar panels. Nevertheless, in the context of the other options, obtaining a significant amount of carbon-free power from solar energy seems to be a reasonable way to fulfill the mismatch between energy supply and demand should the environmental constraints come into play.

At present, there are three technology approaches to producing a "black box" and for the conversion of sunlight into stored energy. Biomass produced through photosynthesis is one such method, but photosynthesis is relatively inefficient, and so biomass farms require extremely large areas per unit of output energy produced. Photovoltaics can be very efficient, but have a large cost per watt of electricity produced. A third approach is the use of semiconductor/liquid junctions, which is an active area of research in my group at Caltech as well as in others around the world. Each approach has its own advantages and issues to be dealt with.

The current situation with solar electricity from photovoltaics is that industrial production is capacity-limited. However the entire industry is currently subsidized. It is a high growth industry, but off of a small base from the viewpoint of total energy production. Solar electricity is cost-favorable in certain off-grid locations, but requires a systems solution to be fully integrated in an energy demand situation, not only producing electricity to the end user.

The next slide presents a plot of the efficiency of photovoltaic devices versus per year. Efficiencies are increasing, but nevertheless, the industry as a whole is still exploring all five of the technology options presented in the slide. The reason for this is that the technologies all lie on a common curve of the cost per watt, as shown on the next slide. Inexpensive materials do not produce very efficient photovoltaics, and the expensive materials produce efficient solar cells, but the cost per watt installed of both systems is about the same to within a factor of 20-30%.

The underlying reason for this roughly equal cost/watt trade-off is that the photovoltaic materials now available basically all suffer from the same fundamental physical limitation, shown in the next slide. The fundamental physical limitation is that the large grain materials, the pure materials, which have a long lifetime so that they can make efficient solar cells, are costly to produce. One can not reach the economies of scale that are characteristic of the silicon semiconductor industry, where one extracts more and more performance out of smaller and smaller areas. The materials cost dominates in energy conversion applications because installed capacity scales linearly with area of the device. Put simply, one needs to pay the price to produce more material to cover larger areas. Alternatively, if one uses cheap materials that have small grain sizes, then these grain boundaries act as recombination sites, and all the known cheap materials make inefficient solar cells. The net result is that one can ride anywhere on this cost/efficiency trade-off, but nevertheless ends up with the same figure of merit, within a factor of 20%.

A similar tradeoff is found for organic ("plastic") photovoltaics. If pure inorganic single crystal materials, like silicon and GaAs, are replaced with much cheaper organic materials, the materials are inherently disordered and therefore lie on the same cost/watt curve. Such cells are cheaper, but less efficient.

There is no reason that this has to be the case, however. In fact, a cogent argument is that in order to bring this technology down by the needed factor of needed 25-100 to be competitive in cost with other sources of primary power, disruptive technologies, that are very different than the technology curve that is being developed now, are likely needed. From a physics point of view, there are at least two approaches that have potential to provide such a technology solution. The first approach is to find chemical methods to fool these inexpensive materials into performing as if they were expensive single crystals, without actually incurring the costs to grow the expensive crystals themselves. This approach involves chemically treating these inexpensive materials so as to fool these grain boundaries into thinking they are part of the periodic crystal that this material is trying to emulate. The other approach is to relax the physical constraint and produce so-called interpenetrating networks. Such an approach relaxes the usual constraint in which the carriers that are excited must exist long enough in their excited states to traverse this entire distance of the cell. Instead, the materials consist of a network of interpenetrating regions. There are two examples of these approaches that are just emerging; neither of them are economically or technologically viable today, but they seem like a right approach in the long run. In the end, the approach has to be almost as cheap as painting your house, as engineered as making layers of film, and as mass producible as both of these technologies. This can likely only be done by implementing the strategies discussed above for moving off of the cost/watt curve that is characteristic of the existing technologies.

So what would we do with all of those electrons even if we could generate them inexpensively from sunlight? Pump them through wires? I have already made the case that we wouldn't know what to do with so much electrical power if we had it, couldn't store it if we did produce it, nor do we want it all as electricity. One approach is to run the electrons to electrolyzers and make H_2 from water. But it is not at all clear that one would use the H_2 so generated as the actual energy carrier. For example, good catalysts already exist that can take H_2 and CO_2 and produce methanol. Methanol can thus be viewed in essence as liquid methane or alternatively as liquid hydrogen (at some sacrifice of energy content of course either way). Methanol is readily transported as a liquid, or could be converted into dimethyl ether, which can then either be refined into other liquid fuels or used directly as a fuel. The methanol could also be used in direct methanol fuel cells if they develop further. Such an approach would be carbon-neutral because the H_2 was generated from a renewable resource, the CO_2 was fixed to generate the fuel, and the fuel is then burned to regenerate the CO_2 to complete the cycle. Note that this is very different than a CO_2 sequestration approach (if sequestration proves viable on the needed space and time scales), in which only a non-carbon based fuel (presumably H_2) can be distributed in order to avoid emitting net CO_2 into the atmosphere. In the renewable energy-based approach to delivering primary power, it is not clear at all that a hydrogen-based economy would be preferred or adopted over a liquid carbon-based fuel economy similar to the one that is currently in place. However, in either case, chemical routes to conversion of electron-equivalents into fuels, being either H_2 in one case or CO_2 reduction to methanol or other carbon-based liquids in the other case, are a critical part of the overall energy system that would be needed to make this approach function effectively. Put simply, use of large amounts of solar energy as a primary power source will require new chemically based technology to effectively and inexpensively absorb and convert solar energy as well as new chemical technology to inexpensively produce useable chemical fuels to transport and deliver this energy to the end-user.

It is also useful to compare "artificial photosynthesis" in which inorganic or organic materials, such as those used in photovoltaics, are used in an integrated system to produce fuels as described above, with modification of natural photosynthesis, i.e., bioengineered plants and bioengineered biomass farms, to produce fuels. Both are solar energy farms broadly defined. As described above, the total land area globally with crop production potential that is not needed for food for 10 billion people is approximately 1.2×10^{13} m^2. At a mean insolation of 200 W/m^2, a solar energy farm must operate with a minimum of 0.7% efficiency if all of this available land is to provide 20 TW of power.

Currently, biomass farms are significantly less efficient than this value as determined by dividing the energy content of the output fuel actually produced by the plants into the incident solar energy striking a unit area of the farm. Hence biomass technology as it is currently implemented is not capable of providing 10-20 TW of carbon-free power terrestrially.

If a bioengineered photosynthetic biomass system were however developed that would reach 5% net conversion efficiency, (a factor of 10-100 better than existing net biomass conversion efficiency), then covering 30% of the cultivatable area on earth would produce 20 TW of power output. Whether that system is a bioengineered system that uses nature as a basis for the starting point, or an artificial photosynthetic system that uses inorganic materials as the starting point (for example producing hydrogen using inorganic materials to absorb the light and generate the fuels) is not an essential point, except that if the system is artificial and is not based on living plants, then of course the land need not be cultivatable or cultivated, so a wider choice of land use and siting possibilities are enabled, and water resources would not limit the deployment of the energy-generating technology. And if the system does use genetically modified living plants, presumably ones that are black instead of green so as to better overlap with optimal wavelength for harvesting the energy of the solar spectrum, then one needs to ask whether society will accept and endorse covering large fractions of the global land mass with plants that are genetically engineered so as to be optimized for energy production.

In summary, it is clear that there will be demand, driven by population growth if nothing else, for large additional amounts of primary energy. The case for significant, and perhaps daunting, amounts of carbon-free energy seems plausible. It is clearly linked to the externality of greenhouse gas constraints. If one does not submit to the driver of the environmental impacts, then we have enough resources and reserves at some reasonable cost to meet the demand with fossil energy. We might not choose to use fossil energy for this purpose, but the need for large amounts of carbon-free power is clearly linked to the environmental constraint at this point in time. A challenge for the chemical sciences is to provide a disruptive solar technology to meet that scale of the problem on terrestrial installations in a reasonable area globally. But such a technology most likely has to be much less expensive, and in a different form, than is available now. Additionally, we need to provide the new chemistry to support an evolving energy mix if we are going to produce this much carbon-free power.

I will close this discussion with the one recommendation. What is important here is to assess the level of risk that we are willing to tolerate with respect to this environmentally driven externality. If we believe that there is a substantial chance that this externality will not come into play, then we should have a prudent, perhaps moderate, level of investment in this alternative technology development approach. If we are not willing to tolerate a very significant level of risk, i.e., if we believe that the effects will, or likely will, come in to play, then one can make a very strong case that the amount of R&D that we need to do in this next 10-20 year period must be significantly higher than what we are doing now, because we do not have the price signals in place to command the R&D from the private sector at the present time nor do we expect to have such in the near future. What we must do is have an informed discussion of how much risk we are willing to live with, and then adjust our level of investment commensurate to being comfortable with that level of risk, with respect to developing globally scalable and economically viable technologies capable of producing 10-20 TW of carbon-free power by the mid-21st century.