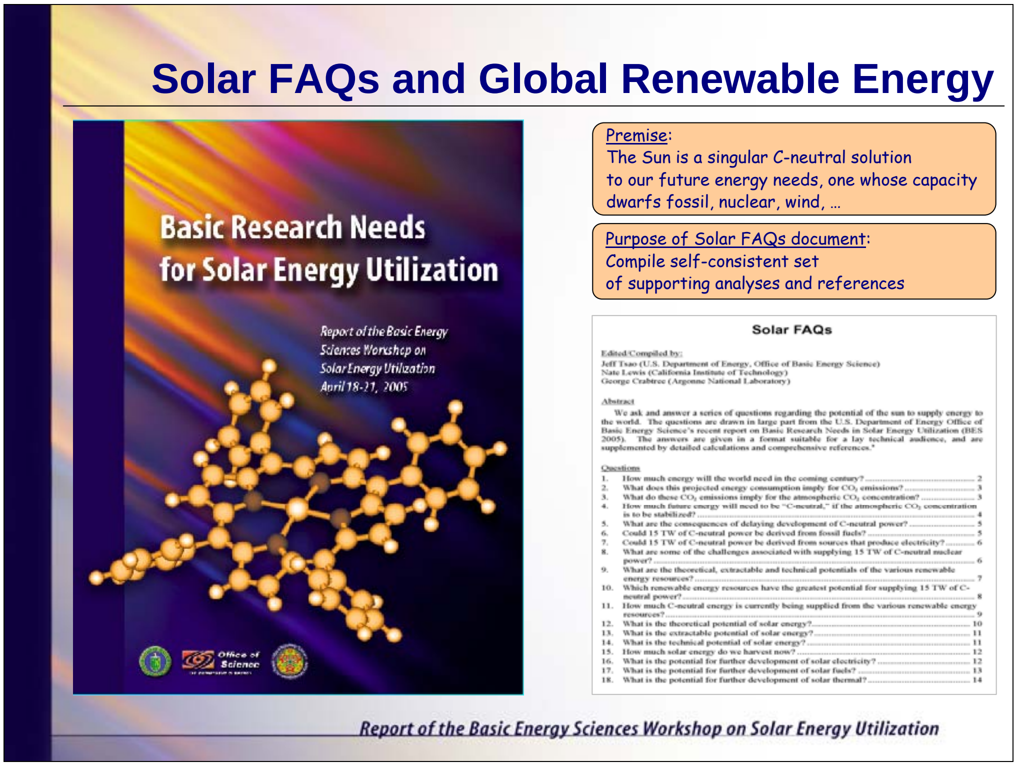
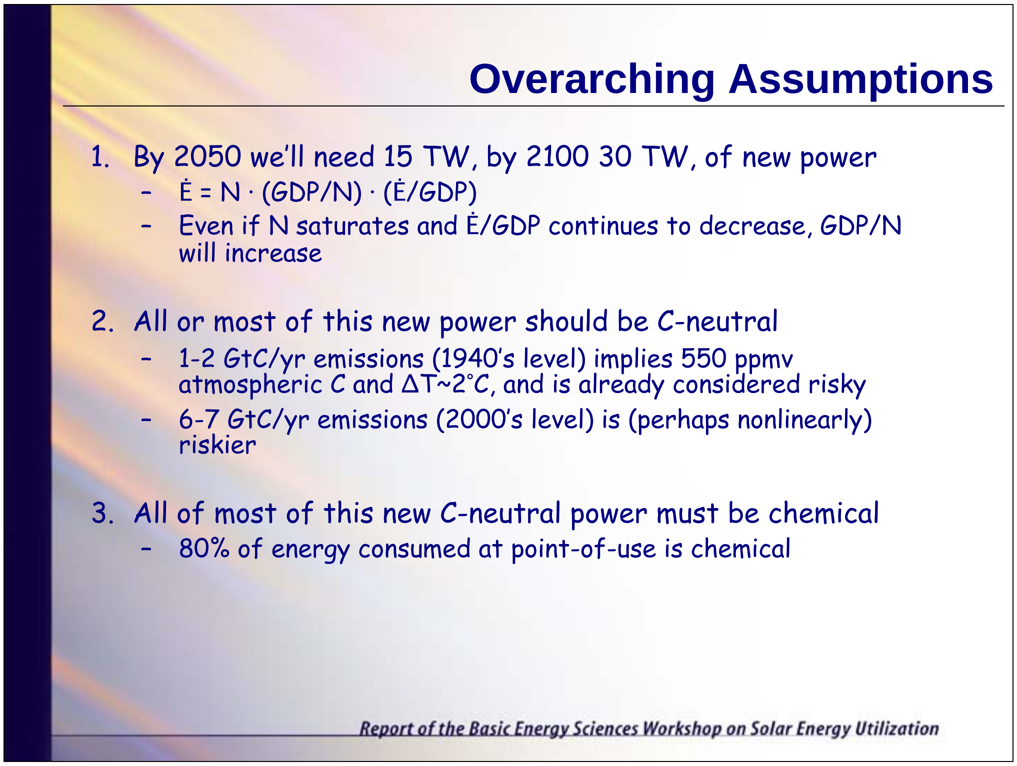


•In this half hour, I'll give a brief overview of our Solar FAQs document, with an emphasis on those parts of the document that touch on the global potential of the various renewable energy sources.

•This document was an outgrowth of last year's workshop on Basic Research Needs for Solar Energy Utilization, chaired by Nate Lewis and George Crabtree. The premise underlying the workshop was, as written here, that the sun is a singular C-neutral solution to our future energy needs, one whose capacity dwarfs fossil, nuclear, wind, etc.

•The purpose of the Solar FAQs document was simply to compile, in as self-consistent a manner as possible, for a lay technical audience, the analyses and references that support that premise. It turns out self-consistency isn't all that easy to achieve, so the document has gone through some twists and turns, and I'm sure will go through more twists and turns. Hopefully, additional insights will emerge from today's discussion.



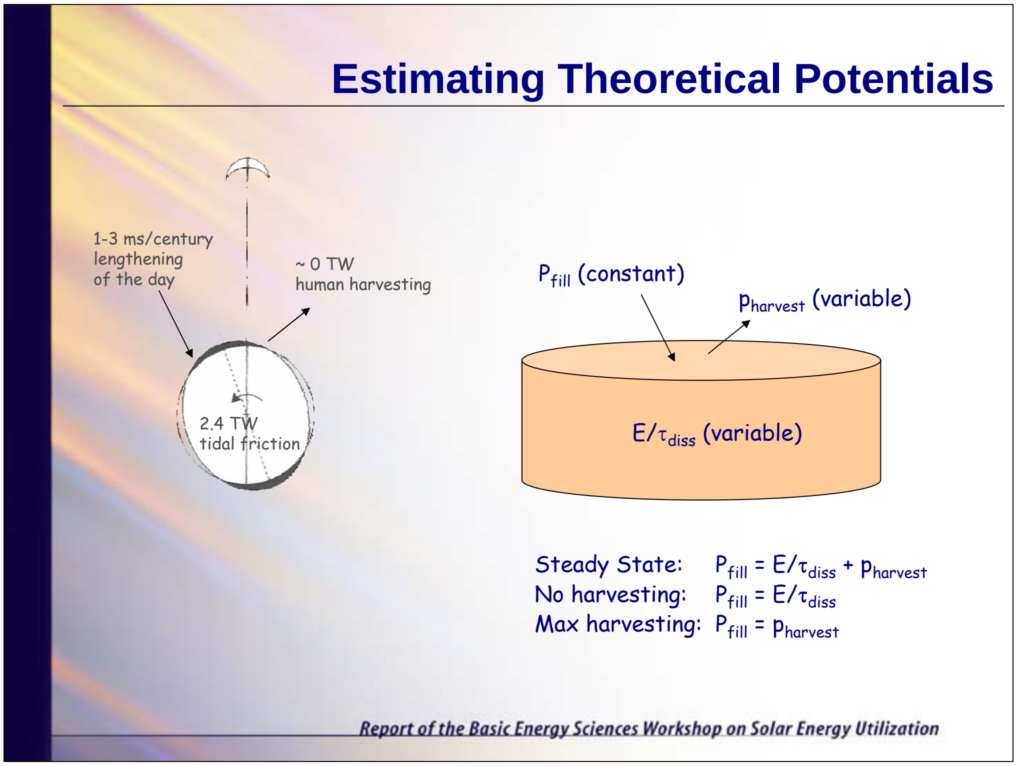
•Let me start with a few of the overarching assumptions of the document.

•Assumption 1 is that, in the coming century we'll need a lot of power. You've all seen this argument before. Basically, even if population saturates, and even if energy intensity continues its steady decrease as technology advances, there is no way to hold back an increase in per capita GDP, particularly as the undeveloped nations develop. So even moderate scenarios indicate that by 2050 we'll need something like 15 TW, and by 2100 something like 30 TW, of new power.

•Assumption 2 is that if we're serious about doing something about global warming, then all or most of this new power should be C-neutral. Again, you've all seen this argument before. Basically, in steady-state, simulations indicate that a carbon emissions rate of 1-2 GtC/yr (characteristic of the 1940's) would lead to an atmospheric carbon concentration of 550 ppmv, and that this carbon concentration is already risky. A carbon emissions rate of 6-7 GtC/yr (characteristic of the 2000's) is much riskier, perhaps nonlinearly so. So eventually we'd like to reduce the carbon emissions rate to its 1940's level. That's impossible, of course, so in the meantime we'd like at least not to increase the carbon emissions rate beyond what it is now. The only way to do that is for all or most of the new power we will need to be C-neutral.

•Assumption 3 is that all or most of this C-neutral power must be chemical. The reason is that, even though electricity is a growing fraction of the energy we consume, most of the energy we consume, about 80%, is still chemical.

•So, putting all of this together, the Solar FAQs document basically assumes that we are looking for 15-30 TW of C-neutral chemical power over the next 50-100 years.



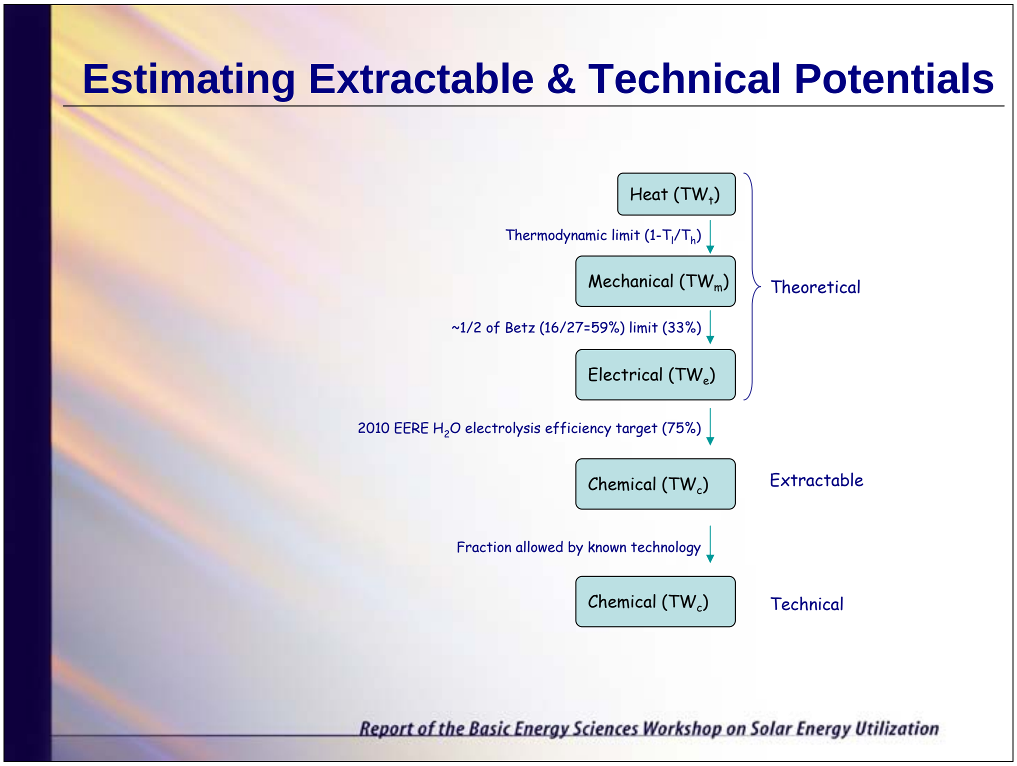
•With those overarching assumptions in mind, let me spend a few minutes on the methodology we used to estimate global potentials, starting with the theoretical potentials.

•Here, we took the following order-of-magnitude approach. For whatever energy source, think of it as a reservoir of energy with a constant fill rate, a variable human harvesting rate, and a variable internal dissipation rate. In steady-state, the fill rate is balanced by the harvesting and internal dissipation rates. If the harvesting rate is zero, the fill rate equals the internal dissipation rate. If the harvesting rate increases, then the internal dissipation rate decreases to compensate, and in the extreme limit the harvesting rate equals the original internal dissipation rate, and the actual internal dissipation rate vanishes.

•For example, for ocean tidal energy, the reservoir is being filled from the earth-moon gravitational system – which loses energy at a rate that corresponds to a 1-3 ms/century lengthening of the day. Since there is no appreciable harvesting right now, all of that energy is being dissipated by frictional forces in the ocean water flows. That rate has been inferred from bottoms-up satellite altimetry measurements to be roughly 2.4 TW. If the harvesting rate were to increase, then the internal dissipation rate would decrease, and in the extreme limit, the maximum harvesting rate would be the original dissipation rate itself, or 2.4 TW.

•This can't really be true, of course, since the fill rate won't be constant as the human harvesting rate increases. Such large scale harvesting of tidal power would change significantly the topography of the ocean – these tidal bulges would vanish -- and would likely change the fill rate from the earth-moon gravitational system. But to calculate exactly how seems pretty tricky.

•So, for this order-of-magnitude exercise, we've simply assumed that the fill rate is constant and equal to the maximum human harvesting rate, and that it represents the theoretical potential of the energy source.



•Now, the energy in these various renewable energy reservoirs comes in all sorts of forms. Ultimately, though, we are interested in how much chemical energy could be extracted from the reservoir, and whether it could make up a significant chunk of 15-30 TW.

•So we need to assume conversion factors from the various types of energies into chemical energy. The conversion factors we are currently using are listed here.

•If we start with heat, then we assumed a Carnot-like efficiency for conversion into mechanical energy (e.g., a moving fluid).

•If we start with mechanical energy, then we assume an efficiency of 33% for conversion into electrical energy. This is slightly more than half of the so-called Betz limit of 59%. One might argue that there is room for improvement of this efficiency towards the Betz limit, so suggestions for what conversion efficiency to use here are most welcome.

•If we start with electrical energy, then we assume an efficiency of 75% for conversion into chemical fuel. This is roughly the 2010 EERE target for H2O electrolysis efficiency. One could argue both ways on this: electrolysis efficiencies could be higher, but right now efficiencies are more like 66%. Again, suggestions for what conversion efficiency to use here are most welcome.

•The end result of this cascade of conversions is something that might be called the extractable potential. This is the power that, in principle, we might be able to extract from a particular energy source, regardless of whether it is possible with known technology or not.

•Now, of this potential, only a fraction will be harvestable using known technology, and this fraction we call the technical potential. What's tricky here is that even if a technology is known, it may range from astronomically expensive to ballpark-but-not-quite economical to already economical. Where one draws the line is the source of a lot of debate, and makes self-consistency a bit tricky to achieve.

Table of Results

Energy Resource	World				U.S.
	Theoretical Potential (TW)	Extractable Potential (TW_e)	Technical Potential (TW_e)	2001 Supply (TW_e)	2001 Supply (TW_e)
Hydropower	12 TW_m[17]	3.5[18]	1.2[19]	0.23[20]	0.056[21]
Ocean Wave	34 TW_m[22]	8.5[23]	0.62[24]	~0[25]	~0[26]
Ocean Surface Currents	8.1 TW_m[27]	2.0[28]	0.012[29]	~0	~0
Ocean Thermal Gradient	3.9 TW_t[30]	0.033[31]	0.0033[32]	~0[33]	~0[34]
Ocean Salinity Gradient	3.0 TW_m[35]	0.74[36]	0.074[37]	~0	~0
Ocean Tidal	2.4 TW_m[38]	0.60[39]	0.037[40]	0.000050[41]	
Wind	1,000 TW_m[42]	250[43]	14[44]	0.0050[45]	0.0023[46]
Geothermal	44 TW_t[47]	2.8[48]	1.9[49]	0.0050[50]	0.0016[51]
Solar Electricity	89,000 TW_p[52]	58,000[53]	7,500[54]	0.00015[55]	0.000025[56]
Solar Fuels[j]	89,000 TW_p[57]	61,000[58]	2,500[59]	0.19[60]	0.088[61]
Solar Thermal[k]	89,000 TW_p[62]	19,000[63]	5,600[64]	0.00060[65]	0.00018[66]

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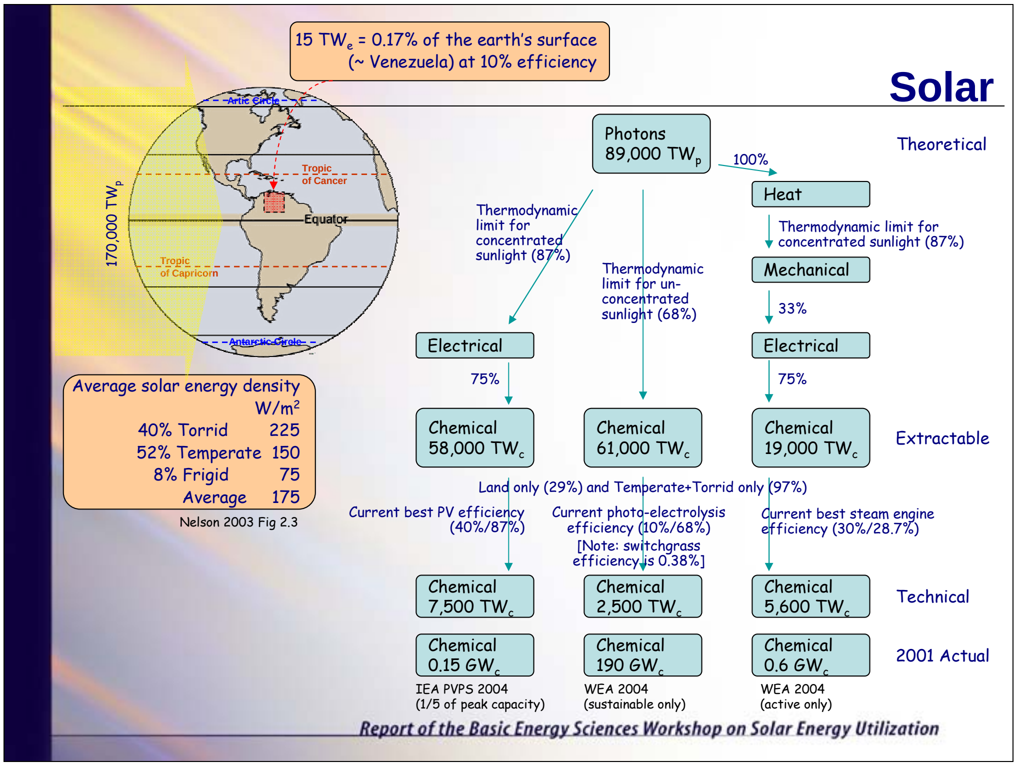
•Here's a table of the results.

•The various theoretical potentials are listed in the left column, with subscripts indicating the kind of energy associated with the source – mechanical, thermal, photons, etc. The various extractable and technical potentials are listed in the next two columns, but now all have been converted into equivalent chemical energy.

•Finally, the 2001 world and U.S. supplies are listed, again, converted into equivalent chemical energy.

•The sources shaded in red are the ones that appear to have potentials in the 15 TW range, and these are the ones I'll go through in the remainder of the slides. I'll go in order from highest to lowest potential, from solar to wind to ocean wave to geothermal.



•Let's start with solar.

•Here, we start with the 170,000 TW of solar radiation that the earth intercepts. Of this, roughly half is scattered or absorbed by the atmosphere, and 89,000 TW is actually incident on the earth's surface. So 89,000 TW can be considered the theoretical potential of solar.

•To get the extractable potentials, we need to convert those photons into equivalent chemical energy, and those conversions will depend on the route.

•For solar electric, we first convert to electricity, which we assume can be done at the thermodynamic limit for concentrated sunlight, or 87%. Then we convert to chemical fuel at 75% efficiency, and end up with an extractable potential of 58,000 TW chemical.

•For solar fuels, we convert directly to chemical energy, which we assume can be done at the thermodynamic limit for un-concentrated sunlight, or 68%, and end up with an extractable potential of 61,000 TW chemical.

•For solar thermal, we convert first to heat, then to mechanical energy, which we assume can be done at the thermodynamic limit for concentrated sunlight, or 87%. After that, the usual route is to convert from mechanical to electrical and then to chemical, which ends up giving an extractable potential of 19,000 TW chemical.

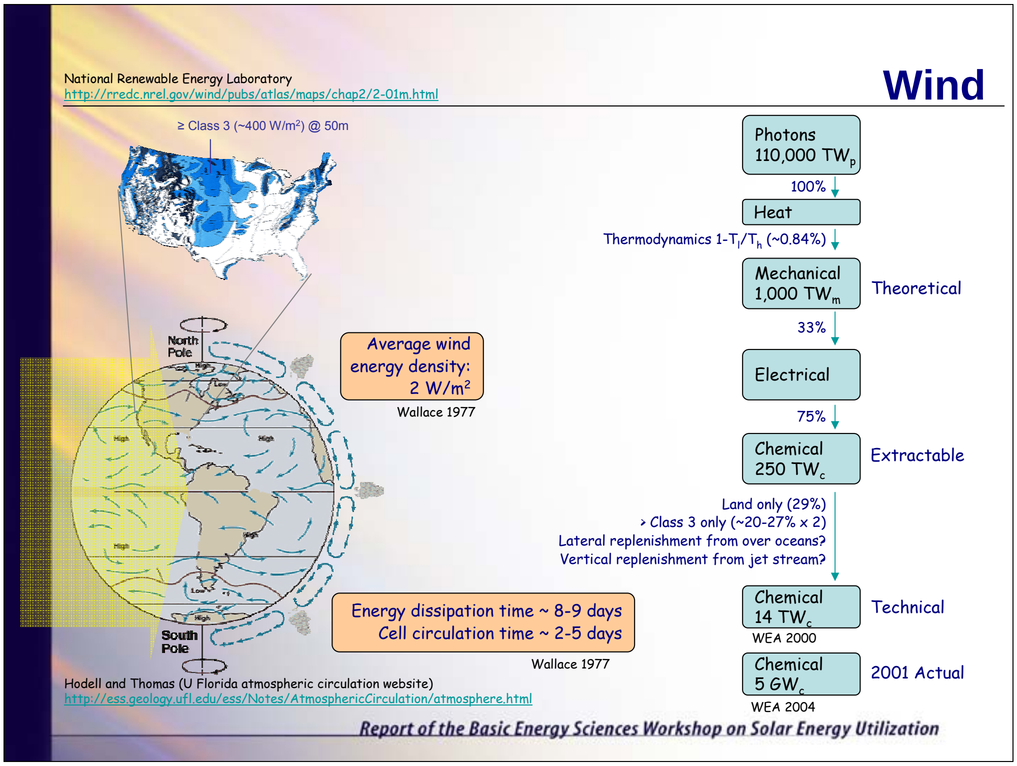
•To get the technical potentials, we make a number of assumptions. First, for all of the solar energies, we assume harvesting only from land. Second, again for all of the solar energies, we assume harvesting only from the temperate and torrid zones.

•For solar electricity, we assume the current best PV efficiency of 40%, which gives us 7,500 TW.

•For solar fuels, we assume the current best photo-electrolysis efficiency of 10%, which gives us 2,500 TW.

•For solar thermal, we assume the current best steam engine efficiency of 30%, which gives us 5,600 TW.

•All of these potentials are, of course, huge, and well beyond the 15-30 TW that we're looking for.



•Now let's consider wind.

•The source of wind energy, of course, is ultimately solar. Air at the earth's equator is warm, so it rises and moves north and south until it hits the poles, cools, sinks, and then returns to the equator. It's not quite so simple, since the earth is rotating, and this rotation causes the circulatory pattern to break up into cells. But, basically, this is just a giant heat engine, with about 110,000 TW of heat input and a very low estimated efficiency of 0.5-1.0%, giving a theoretical potential on the order of 1,000 TW. Averaged over the surface area of the earth, that ends up being roughly 2 W/m2.

•Of course, that theoretical potential is in the form of the mechanical energy of a moving fluid, so after converting to electrical and then chemical energy, we "only" get an extractable potential of 250 TW.

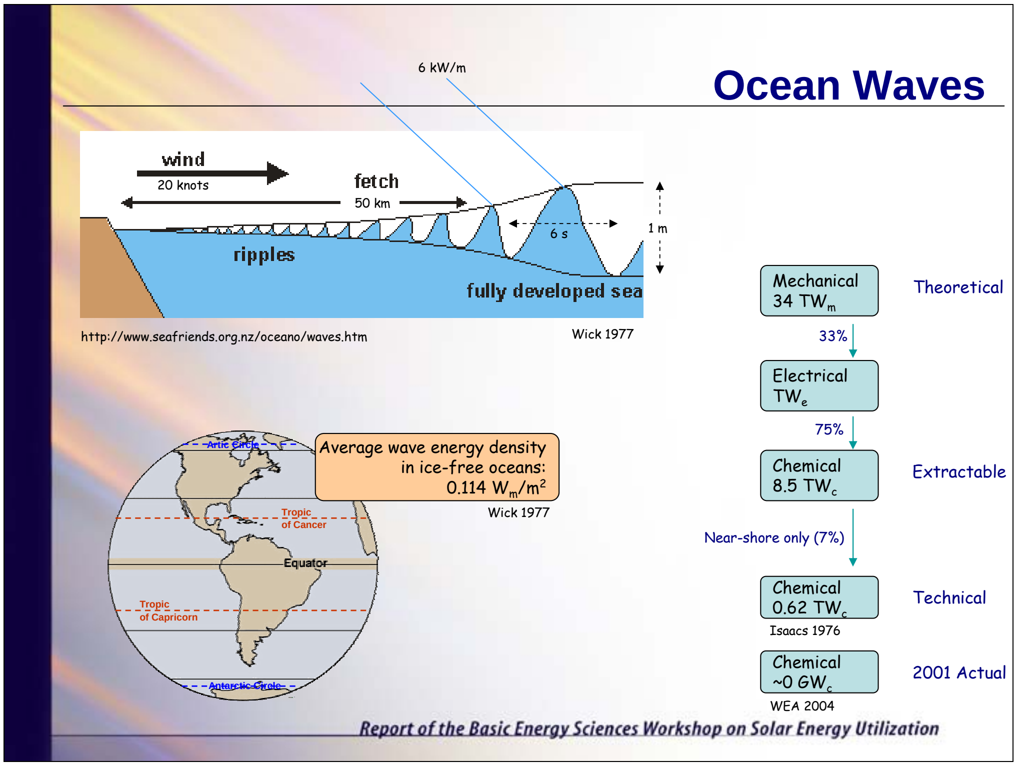
•But now we get to the trickier part -- the technical potential. If one assumes that current technology only enables harvesting over the 29% of the earth's surface that is land, and from the 20-27% of the land area that has reasonably high wind power densities (Class 3 and above, indicated by the blue areas on this map of the U.S.), then we end up with a technical potential of 15-30 TW. That top-down estimate is approximately consistent with a bottoms-up estimate of 14 TW from the Year 2000 World Energy Assessment.

•However, there are reasons to worry about this estimate, mostly hinging on what I think of as the "replenishment" question. Consider one of these circulation cells, and consider two time scales – the time scale for dissipation of the energy in the cell, and the time scale for circulation of the energy in the cell.

•If the dissipation time is much longer than the circulation time, then the energy from places where you haven't sited a wind turbine (like over the oceans) would eventually circulate to places where you have sited a wind turbine, and so by not including the oceans we would have underestimated the technical potential.

•But if the dissipation time is much shorter than the circulation time, then you can only harvest exactly where you have sited a wind turbine, and some power (like that high in the jet stream) becomes un-harvestable, and then we've overestimated the technical potential.

•In fact, simple estimates of the two time scales indicate that they are comparable, so I think more thought is needed to get a self-consistent number for the technical potential.

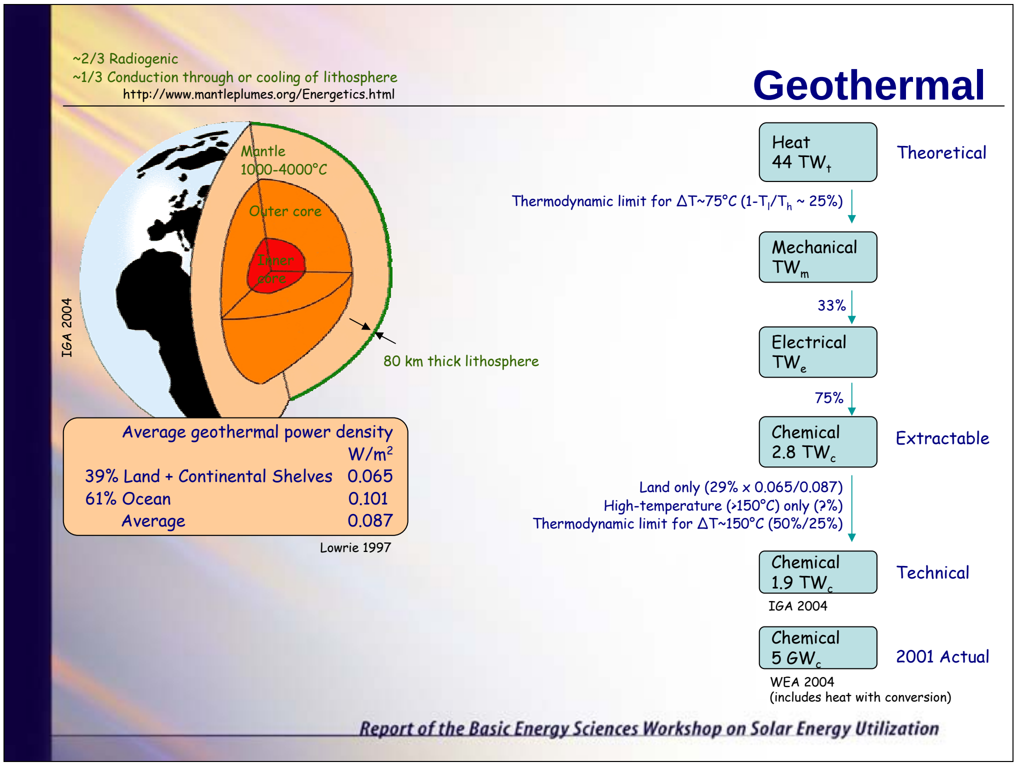


•Now let’s consider ocean waves.

•Just as the source of wind energy was solar, the source of ocean wave energy is wind. If we assume a global average wind speed of 20 knots, then the resulting average wave energy density can be calculated to be about 0.1 W/m2. That’s about 20x less than the energy density of wind, and about 2000x less than the energy density of solar, so we can expect all of these numbers to be proportionately lower.

•If we integrate that 0.1 W/m2 over the ice-free oceans, then we get a theoretical potential of 34 TW. If we convert to electrical and then to chemical energy, we end with an extractable potential of about 8.5 TW of chemical energy.

•Finally, if we assume current technology only allows for harvesting from the near-shore areas, then we end up with a technical potential of 0.6 TW.



•Finally, let's consider geothermal.

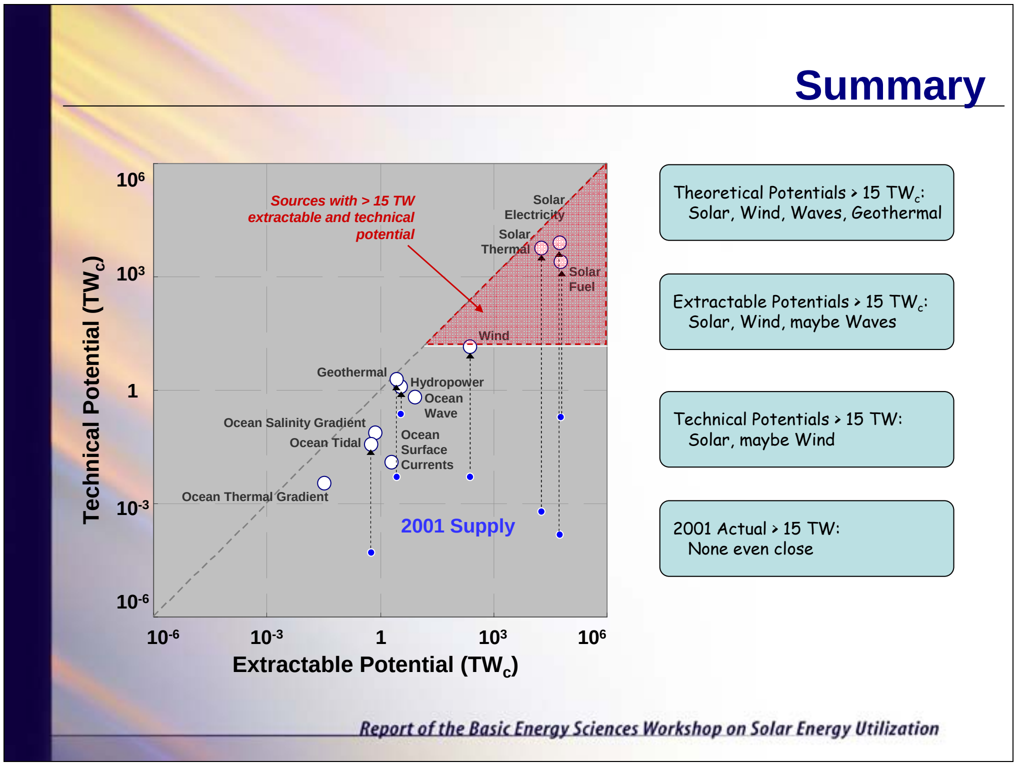
•This is one of the sources that doesn't ultimately derive its energy from the sun. Instead, about 2/3 of it is from radioactive decay of elements in the earth's crust, and about 1/3 of it is due to either conduction through, or cooling of, the earth's crust.

•All together, the heat emerging from the earth's crust has a power density of about 0.087 W/m2. This is comparable to that for ocean waves, so we can anticipate somewhat similar numbers for their potentials. In particular, its theoretical potential, integrated over the earth, is pretty large – 44 TW.

•However, geothermal has the disadvantage that in most places it appears as low-grade heat, so after you convert from heat to mechanical and then to electrical and chemical energy, you end up with an extractable potential of only about 2.8 TW.

•Like wind, however, the technical potential of geothermal seems to be a little tricky, and again we haven't come to closure on it. If one harvests only from land, and from the fraction of the land area that represents high-grade heat (greater than 150C), then we end up with a technical potential of less than 1 TW. However, a bottoms-up inventory by the International Geothermal Association estimates 1.9 TW, so there is a discrepancy that needs to be looked at. It's possible the discrepancy is related to the assumption here of long-term (geologic time scales) steady-state, while the IGA assumption is that you harvest local hot spots, and as they're depleted, you move on.

•Of course, for our original purpose, we may now be starting to split hairs, since it is clear that geothermal doesn't even approach the 15-30 TW of power we are looking for.



•So, here's a summary, illustrated on this plot of technical vs extractable potentials.

•There are four renewable energy sources with a global theoretical potential greater than 15 TW: solar, wind, waves and geothermal.

•After conversion to equivalent chemical energy, however, there are only three with a global extractable potential greater than 15 TW: solar, wind and maybe ocean waves.

•But after taking into account known technologies, there are only two with a global technical potential greater than 15 TW: solar, and maybe wind.