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DEPLOYMENT PROSPECTS FOR PROPOSED SUSTAINABLE ENERGY ALTERNATIVES IN 2020

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ABSTRACT.

We present brief comparative economic and environmental appraisals of the alternatives that have received the most attention in recent years: conventional biofuels (agrofuels), cellulosic ethanol (CE), microalgae, electric vehicles (EVs), plug-in hybrids (PEHVs), compressed natural gas (CNG) vehicles, "semi-clean" (SCPC) coal, clean coal, wood co-firing, nuclear, photovoltaic solar (PV), concentrated solar power (CSP), geothermal, hydropower, wind, and a novel alternative energy solution known as "WindFuels". Critical reviews of the projections of both Levelized Cost of Energy (**LCOE**) and life-cycle CO_2 emissions of these primary alternatives for clean, sustainable energy are presented.

We identify and review the major challenges faced by these alternatives – many of which have received incomplete treatment in previous studies. Then from the projected LCOE, carbon neutrality, resource availability, technological challenges, and recent market data; the probable growth rates for the various alternatives are projected, and the environmental benefit and economic burdens associated with these alternatives are assessed.

1. INTRODUCTION.

The need to increase our efforts at solving the climate and energy challenges is clear; but the *economic* climate has changed dramatically since mid 2007. The world is still dealing with the worst recession in three quarters of a century, and the economic crisis would be worsened by poor choices with respect to sustainable energy alternatives. It is essential that much more effort be put into critical review of the projections of both Levelized Cost of Energy (**LCOE**) and life-cycle CO_2 emissions of all proposals for clean, sustainable energy. The surge in funding by both private and public entities for deployment of early-stage technologies seen in recent years cannot be sustained by uncompetitive alternatives or by options now known to have more serious environmental consequences than appreciated several years ago.

We have identified a number of major challenges that have received incomplete treatment in previous studies. Examples include: (1) very small climate and net-energy benefits from conventional biofuels, other than for tropical sugarcane; (2) long-term carbon loss in untilled soils from steady harvesting of forests or grasslands; (3) lack of progress toward achieving positive energy balance in all algal-oil demonstrations thus far; (4) rapidly increasing drilling costs for enhanced geothermal systems; (5) rapidly escalating prices for new nuclear power plants; (6) high hidden costs associated with all battery technologies; (7) expected rapid rise in cost of biomass for co-firing; (8) little progress in cost reduction of CSP; (9) slow progress in reduction of installed costs of PV; and (10) extremely low efficiencies, short lifetime, and high costs in solar-driven carbon-conversion demonstrations.

We can calculate the levelized cost of energy (LCOE) for an alternative energy platform based on its capital cost, fuel costs, O&M costs, capacity factor, and expected lifetime. As we will argue from a combination of economic and climate reasons, the potential of wind has frequently been underestimated, while the CO_2-abatement potentials of biofuels, CSP, battery electric vehicles, and geothermal are often over estimated by more than an order of magnitude [*1*]. Some recent studies from perspectives within the developing world have been even more pessimistic than ours with respect to biofuels and agrofuels [*2*]. Median estimates of the potential of the other alternatives tend to agree more closely with our appraisals.

Figures 1 & 2 put the components of the climate-change challenge into perspective. **Figure 1** shows total greenhouse gas (GHG) emissions by sector [*3*], while **Figure 2** shows the energy consumption and sources for the U.S. (these ratios are similar to what is seen internationally) [*4*]. Clearly, major reductions from all sectors (not just power plants and vehicles) are essential to achieve the targets of 20% reduction in GHG emissions by 2020 (5.6 Gt-CO_2/yr) and 50% (14 Gt-CO_2/yr) by 2050.

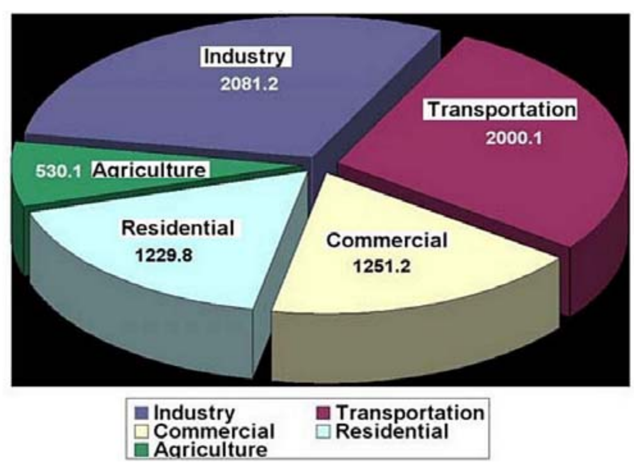

Figure 1. Sources of U.S. greenhouse gas emissions by sector.

In the following analyses, our projections take into consideration the projected LCOE, carbon neutrality, resource availability, technological challenges, and recent market data of each alternative. We expect that the increased CO_2 mitigation from the growth in wind, hydropower, semi-clean coal, wood co-firing, and nuclear will be 5.4 Gt-CO_2/year by 2020. All other energy alternatives combined will mitigate less than 0.4 Gt-CO_2, though in some cases the alternatives are in their infancy and represent much greater future potential. Increased use of natural gas, coal, and oil in the developing world by 2020 will likely exceed 10 Gt-CO_2. Of course, a recession of the severity seen in 2008 could again reduce CO_2 emissions by 1 Gt/yr.

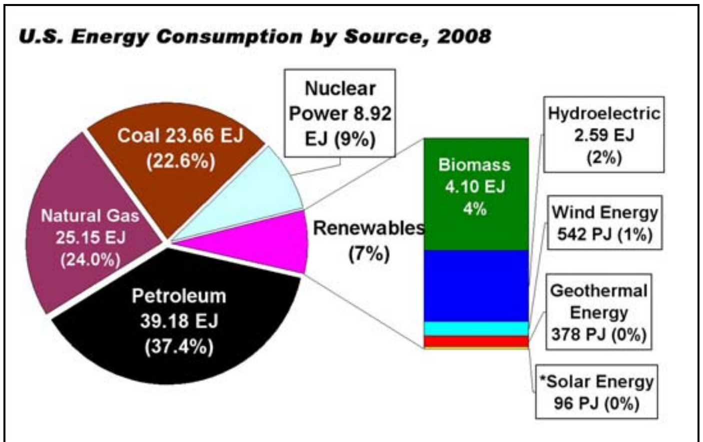

Figure 2. Sources of U.S. primary energy consumption. The solar energy figure includes thermal energy gathered through solar heating.

The data from the rapidly changing market conditions between 2010 and 2015 will be essential before meaningful predictions of the period from 2020-2030 could be possible. Therefore, we offer very few comments with respect to the time horizon beyond 2020

2. TRANSPORTATION FUELS.

The doubling in the price of oil in 2009 serves again to remind us that conventional oil is a limited energy source and must gradually be replaced. **Figure 3** shows the current contribution of unconventional fuels. Note the high-carbon unconventional fossil transport fuels (tar sands, extra heavy oils, coal-to-liquids (CTL), gas-to-liquids (GTL), oil shale, and others). These high-carbon fossil fuels will grow in tandem with biofuels and other carbon-neutral transportation fuels as the reserves of conventional crude gradually go dry. So any carbon offset from new fuels production could largely be undone by growth in other high-carbon transport fuels for at least the next decade.

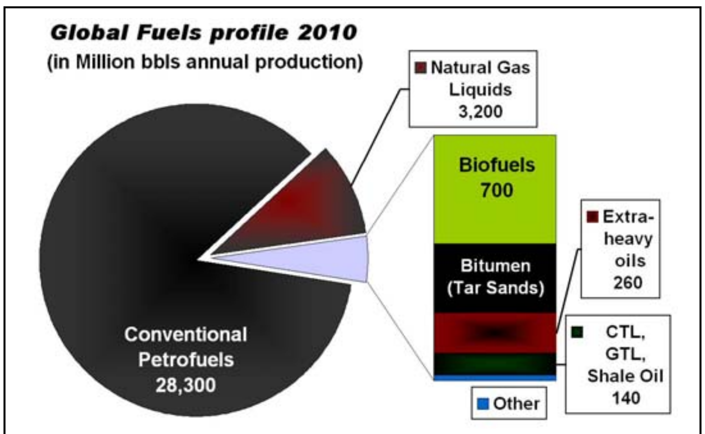

Figure 3. Biofuels are still only a small piece of the pie.

However, these high-carbon fuels are also the most expensive fuels. In the fungible global oil market, the most expensive fuels will be the first displaced by alternative options. Therefore, we assign a carbon abatement credit for alternative fuels as though they would offset fuel produced from tar sands – which, for tar-sands gasoline, has a total carbon intensity of 106 t-CO_2/TJ [*5*].

2.1 CONVENTIONAL BIOFUELS/AGROFUELS.

The 9B gal of ethanol produced in the U.S. in 2008 contributed about 3% to the total US liquid transportation fuel energy (225 Bgal of gasoline, diesel, and jet fuel) [*4*], but the net energy contribution was only about 25% of that, or 0.7%, because of the fossil fuels required for biofuels production [*2-9*]. The most recent research indicates the climate benefit (CO_2 reductions) for corn ethanol is between negative 5% and positive 16% (depending on the time period and discount rate) relative to conventional gasoline – which has a total carbon footprint of about 92 t-CO_2/TJ when upstream contributions are included [*5*]. That is partly due to the effect of land-use change [*2, 6, 9-12*]. The mean of two recent EPA determinations (for 30-year and 100-year horizons) puts the life-cycle carbon neutrality (CO_2 emissions reductions) of US domestic biofuels at 7% [*6, 12*]. Therefore, the net reduction in CO_2 release that can be credited to biofuels in the US in 2008 was 17 Mt-CO_2 [*13*]. Assuming a 15%/yr improvement (from the combination of growth and technology advances), conventional biofuels could be reducing domestic CO_2 emissions by 92 Mt-CO_2 /yr in 2020.

The negatives associated with agrofuels (the word preferred for large-scale biofuels by giant corporations) are much greater than is generally appreciated [*2, 6, 10*]. The recent study by the NAS/NAE/NRC estimates the "hidden costs" (mostly health-related) of conventional biofuels to be 25% greater than those associated with conventional gasoline [*6*]. The Food First Institute [*2*] and UN sponsored studies have all concluded that agrofuels directly contribute to global hunger. For perspective, consider that a gallon of gasoline contains ~130 MJ (31,000 kilocalories – or Calories). Therefore, if agrofuels were produced at 50% efficiency, using one gallon of gasoline equivalent (gge) would consume as much food as 31 healthy adults eat in a day. The average U.S. citizen uses 2 gge/day of liquid fuels. Currently agrofuels consume ~18% of the world's food to produce ~2% of the world's liquid fuels. Massive scale-up of agrofuels will obviously be limited, compete with nutrition needs for food, and will require enormous land use change. Scale-up will also contribute to issues such as herbicide and fertilizer runoff [*2, 14*] – that are credited to industrial agriculture. These observations imply that our growth and carbon-mitigation estimates for biofuels (92 Mt-CO_2/yr in 2020, or 75 Mt-CO_2/yr above 2008) are optimistic, and may represent close to the ultimate potential of this resource.

Advocates contend there will be transformational advances in cellulosic ethanol and algae oil. We show below that neither will match conventional biofuels for at least the next 15 years, either with respect to LCOE or CO_2 emissions abatement.

2.2 CELLULOSIC ETHANOL (CE).

Current CE plants (only small pilot plants are yet in operation) achieve under 35% efficiency – or about 70 gallons of ethanol per ton of bone-dry feedstock [*15*]. Efficiencies are expected to reach 50% in large plants fully optimized for their specific feedstock in a few years [6, *16*], which would still produce only 100 gal of ethanol (9.1 GJ) per ton of dry feedstock [*6*]. A hundred gallons of ethanol contains 156 kg of carbon – only 29% of that in the ton of feedstock from which it was made. Most of the rest of the carbon is emitted as CO_2. Some of this would have been sequestered in soils, trees, or forest floors. Most life-cycle analyses of CE have not adequately considered the affects on reduced natural sequestration of biocarbon [*17*].

Figure 4 illustrates the near term contribution of advanced biofuels. The global annual CE production by late 2011 may be ~50 Mgal/yr, but many of the planned larger CE projects have been scaled back [*18*]. Coskata, considered a leader in the field, has recently begun operation of a new $40M plant that is expected to ultimately reach 40,000 gal/yr [*19*]. At a 7% discount rate, plant amortization alone would be ~$80/gallon. However, these costs should be reduced in large plants. Poet has recently announced a 25 Mgal/yr cob-fed plant that may come on line in 2012 and is projected to cost $250 million [*20*]. The amortized capital costs in that case (again at 7%) would only be ~$0.80/gallon. This is fairly consistent with other studies that suggest capital costs plus O&M costs will be ~$1.5/gallon [*14*]. However, some CE researchers are expecting the cost of just the cellulase enzyme to remain above $1.50/gal of ethanol for many years.

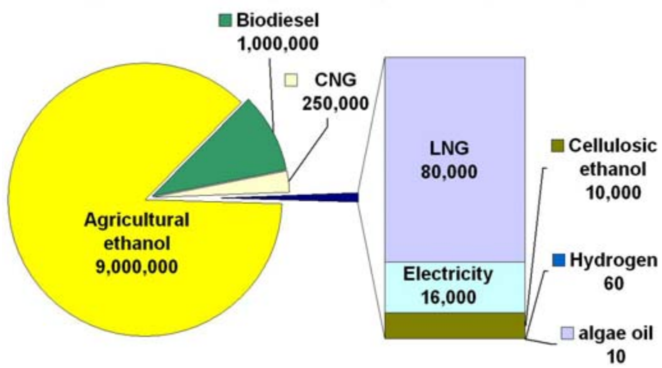

Figure 4. Projected American alternatives contributions in 2010 in thousands of gallons of gasoline equivalent.

Delivered feedstock prices have increased by a factor of 8-15 from the $10/ton projected in 2002, or by a factor of four from 2005 projections [*21*]. Mean price projections for delivered, dry, biomass increased from $35/t in 2006 to $100/t in late 2009 [*14*]. We expect mean biomass costs will be $400/t ($24/GJ, or 60% that of oil at $240/bbl) by 2020 and beyond. At 50% efficiency, the feedstock costs alone for CE would then be $4.40/gal.

There may be sufficient low-cost crop residue to support a few dozen 25 Mgal/yr plants with delivered feedstocks near $110/ton. In that case, their ethanol could cost as little as $2.40/gal to produce. However, if farmers sell their crop residue more often than every fourth year, they will have to apply more fertilizer and accept more rapid loss of topsoil [*2, 10, 14*]. Therefore, a mean corn stover annual harvest will be about 2 t/ha/yr [*14*]. For reference, corn yields are about 9 t/ha/yr, and the price of corn was about $160/t in late 2009. The low yield along with the low density of baled corn stover (one-fourth that of corn) make dealing with it unattractive to most farmers.

Wood pellets are currently about $200/ton [*22*], but their prices too will begin to soar in several years [*23*]. The capital requirements for co-firing are much less than for CE, so co-firing should grow much more rapidly and soak up the available supply of cheap woody feedstocks. The domestic potential co-firing demand exceeds the 500 Mt/yr biomass supply that has been projected to be possible by 2020 [*14*].

CE may grow 30% annually after 2011. If so, it would provide ~500 Mgal/yr in 2020, or 6% as much fuel as corn ethanol does today. This is much less than the recent NRC estimate (8 Bgal/yr in 2020) [*14*]. However, the NRC estimate of the cost of large CE plants is about half that of the only real data point currently available (the promised Poet plant [*18*]). CE scale-up is severely hampered by the major differences seen in enzymatic processing plants (both in the pretreatment stage and in the enzymes) for all major classes of feedstocks (corn stover/cobs, switchgrass, miscanthus, softwoods, hardwoods, alfalfa, and manure). This means the first few plants for each new feedstock will be pilot plants [*14*].

The CO_2 abatement for CE is impossible to estimate accurately, partly because of the unknown sources of the feedstocks. Reasoned estimates of carbon neutrality for next-generation CE range from 2% to 90% [*2, 6, 7, 14, 16, 17*]. Conversion of forest floors or similar "waste" to ethanol results in the immediate release of most of this carbon that previously was slowly oxidizing. The reduced sequestration of biocarbon in natural reserves for several decades following harvesting must be included in the analysis. Soil carbon is expected to decrease about 25% over a period of about 40 years when forests or grasslands go from natural to regularly harvested [*24, 25*]. We believe a realistic estimate with a 40-year time horizon for CE is 40% carbon neutrality. Therefore, if 500 Mgal/yr CE is produced in 2020 (offsetting 330 Mgal/yr tar-sands fuels), a reasonable estimate for CO_2 mitigation from it would be 3.1 Mt-CO_2.

2.3 MICRO-ALGAE.

Biodiesel production from oil crops scaled up quickly (~40%/year) over the past decade to 2.6 billion gallon global capacity by the end of 2008. However, this growth cannot happen with algal oil – notwithstanding the hype from the algae advocates in the past two years [*26*]. About $200M was invested (by VCs and the DOE) in 2008 in algae companies, and another $500M may be invested in 2009-2011. Algal fuels are at least an order of magnitude more capital intensive than biodiesel from oil crops, and there is no evidence that recent investments will result in major cost reductions.

The best results thus far from attempts at moderate-scale algae production achieved 422 GJ/ha/yr lipids bioenergy in their best year [*27*]. That project cost over $26M in current dollars. Had they succeeded in producing algal fuels from the lipids harvested, the resulting biodiesel would have cost ~$40,000/gal. All the algae companies contacted for a recent C&EN report admitted that production costs needed to be brought down by at least an order of magnitude before fuels from photosynthetic algae could compete [*28*]. Several other independent studies have concluded the minimum cost for fuels from photosynthetic algae will be in the $25-60/gal range [*29-31*].

The low-end of current commercial-scale algae for the food industry is $5000/ton, though some is over $17,000/ton [*32*]. Fuel-grade products made from dry algae of mid-range lipid content (35%) at $5000/ton would cost over $50/gal [*33*].

The company Sapphire is expecting it will cost $1B to develop a 1200-acre facility over the next 8 years that may produce 0.8 Mgal/yr of fuels [*34*]. The interest on that investment at 7% would be ~$100/gal. Another analysis concludes amortization alone on capital costs for 500 kgal/yr facilities growing algae in open race-track ponds (the cheapest approach) would contribute $40/gal to the cost of algal oil, and O&M costs could be about $20/gal [*31*]. The O&M costs, in likely order of significance, are: labor, electricity, replacement parts, fertilizers, CO_2, flocculent, water, hexane, sterilizers, etc. [*35, 36*].

Non-photosynthetic algae from waste streams that require treatment for other reasons may offer limited profit [*26*]. However, those opportunities have not yet attracted large investments – perhaps partly because of the difficulty in applying a standard process design to such a wide range of settings. Solazyme raised $50M in capital to make fuels from cheap biomass using non-photosynthetic algae [*37*]. They are expecting to deliver over 20,000 gal of low-grade fuel (ship grade) to the Navy over the next four years at a price of $425/gal [*38*].

No algae approach has yet come close to demonstrating a positive energy balance. In fact, the total fossil input energy (not including the solar) required by a scaled-up process based on best available technology would be 2.3 times the energy in the biodiesel produced [*36*]. A number of the key requirements needed to improve the energy balance have not yet been demonstrated even at the lab scale.

At least a dozen startups are still saying they will produce tens of thousands of gallons of fuel from photosynthetic algae within a few years at low prices [*26, 39*]. Most will probably go the way of GreenFuel Technologies, which burned through $70M while producing only a few hundred gallons of fuel. Still, there will be some algal fuel production within a few years, mostly non-photosynthetic. Our rough estimate is 1 Mgal/yr by 2015. If it then grows (optimistically) at 20%/yr, it could be at 2.5 Mgal/yr in 2020. With the current negative fossil energy balance [*36*], the carbon intensity of these fuels will be worse than tar-sands oil. Therefore, we're projecting the CO_2 abatement potential of algal oil to be negative in 2020.

2.4 PHEVS, CNG, AND PROPANE VEHICLES.

The EV/PHEV enthusiasts think it should be possible to have 6 million EVs on the road in 2020 [*1*]. However, a goal of even one million seems optimistic for several reasons: (1) The PHEV's are projected to have a $15,000 cost premium; (2) few consumers will want to deal with the hassles of daily charging, limited range, and no trunk space; and (3) the hidden costs of EVs are becoming better appreciated. The recent study by the NAS/NAE/NRC estimates the hidden costs of PHEVs in 2020 will be ~20% greater than those associated with conventional-gasoline hybrid vehicles. The NRC study concludes that life-cycle GHGs will be similar, partially because of the large GHG emissions associated with battery manufacture [*6*].

The Toyota Prius was released in 2002 and sold its one-millionth car in April 2008, even though the fuel savings with the Prius pay for its cost premium in as little as 3 years. There may be 50,000 EV's and PHEVs on the road globally in 2012. If the number sold then grows by 20% annually, there would be a total of 1 million on the road in 2020.

Worldwide, there will be about 1.3 billion active cars on the road in 2020. The total liquid fuel savings from 1M EVs and PHEVs in 2020 may be 360 Mgal/yr (they will mostly be used in short commutes). Most studies indicate the CO_2 savings from PHEVs (not counting the battery-manufacturing CO_2 debt) may be 30% compared to HEVs [*1*], but we will further credit them with offsetting 360 Mgal of tar-sands fuels. Therefore, the CO_2 abatement could be 2.0 Mt-CO_2/yr in 2020.

Compressed natural gas vehicles currently account for about 0.11% of transport fuel usage in the U.S. CO_2 emissions per unit energy from the engines are about 30% lower than for standard fuels, but it only takes 1.5% leakage during the tank filling process for the global warming contribution from the leaked methane to completely offset the reduced engine emissions. Reliable data on typical losses during filling are not available. If these losses are 0.5%, then the CO_2 abatement of current CNG usage in vehicles is 0.4 Mt-CO_2 /yr. If, for example, its usage increases by 23% annually, its abatement would be 4 Mt-CO_2 /yr in 2020.

Propane usage in vehicles is at a level similar to that of CNG. However, the propane fossil resource is only about 4% that of methane, and the price of propane should rise rapidly over the coming decade as it steadily replaces naphtha as the preferred feedstock for making ethylene and propylene. The carbon intensity of propane is only 10% better than that of conventional liquid fuels (partly because of unavoidable leakage) [*6, 40*], and its growth potential is very limited.

3. ELECTRICITY PRODUCTION.

Table 1 presents the key cost-related numbers used in our LCOE calculations for grid-power options at discount rates of 5% and 10%, which seem to be reasonable lower and upper boundaries for planning purposes. A 1%/yr output degradation is assumed for the PV and EGS calculations, while the others are assumed to be maintained constant by O&M costs. The numbers shown are supported in the following discussions for the US in 2015 – except that for fusion, which is based on projections for 2040. The number for coal's capacity factor (ratio of mean output to peak output) is only slightly below the recent average, though we anticipate the capacity factor for coal to drop steadily over the next 40 years in areas where wind or nuclear energy is added to the grid, as explained shortly.

3.1 COAL.

The worldwide average efficiency of a coal power plant today is about 31% (higher heating value, HHV). While coal is still the cheapest power source for many regions, its costs are increasing. The 2009 average U.S. price for coal works out to ~\$2.1/GJ_T. The delivered cost of bituminous coal increased by more than 113% since FY2000 [*41*], so we project another doubling in cost for coal energy by 2020. With higher coal costs, a new super-critical pulverized coal (SCPC) 40% HHV plant [*42*] would see an LCOE similar to that from a fully paid off plant built 30-40 years ago getting 27% efficiency. Power companies that see higher-than-mean delivered coal costs would already see a reduced LCOE for replacing their inefficient old coal plants with new higher efficiency SCPC plants. These economic incentives will become more persuasive as the cost of emissions and the cost of coal increase.

The combination of economic incentives, government regulations, low-interest capital, and public pressure could easily lead to 25% of current coal electricity generation being decommissioned and replaced by 2020, as the LCOE of this method of abatement is negative. The old plants would have average CO_2 emissions of 1.15 t-CO_2/MWhr and the new ones 0.8 t-CO_2/MWhr – without sequestration. (Integrated

Table 1. Recent data on U.S. renewable grid-energy costs (11/2009) and Near-term Projections

Resource	C_{PE} (\$/W_{PE})	Capacity Factor *F*	O&M \$/MWh	Cost of Fuel 2015 (per MWh)	Lifetime years	LCOE, 5%, \$/MWhr	LCOE, 10%, \$/MWhr
Wind (prime sites)	1.5	0.35	1	0	40	29	51
Old coal plants	0	0.6	6	42	40	48	48
Prime Geothermal	5.2	0.85	10	0	40	50	81
Wind (good sites)	1.8	0.25	2	0	40	50	86
New SCPC (coal)	2.6	0.7	5	28.5	50	57	76
Hydropower (good sites)	5.5	0.5	1	0	50	69	127
Natural Gas, IGCC	3	0.6	5	40	40	78	103
New Nuclear	8.3	0.85	15	10	40	90	139
Clean Coal w/CCS	5	0.8	8	45	35	92	123
Offshore Wind	4	0.35	6	0	30	90	143
CSP-500MW	4.4	0.29	10	0	30	122	192
CSP-80MW	3.9	0.23	45	0	30	170	249
PV-80MW (Arizona)	6.7	0.19	10	0	30	309	499
roof-top PV (Arizona)	7.2	0.17	20	0	25	402	613
EGS	35	0.85	60	0	30	409	631
roof-top PV (N.J.)	7.2	0.12	20	0	25	561	860
Fusion (in 2040)	70	0.5	50	500	2	8600	9350

Gasification Combined Cycle (IGCC) plants can be below 0.4 t-CO_2/MWhr [*42*], but the price of liquefied natural gas will limit their growth.) Current global coal usage is over 6.5 Gt/yr, which results in the release of about 13 Gt-CO_2/yr. Replacing 25% of global coal power generation with plants achieving 39% efficiency rather than 28% would be equivalent to increased abatement of 1000 Mt-CO_2/yr in 2020.

3.2. CARBON CAPTURE & SEQUESTRATION (CCS).

A number of options are being evaluated for "clean coal" – separation of about 90% of the CO_2 from coal combustion followed by pumping it into deep geological formations. The biggest challenges with CCS are the added capital costs to the power plant and the reduced efficiency – initially 39-42% efficiency loss [*43, 44*], but eventually less than 29% [*43*].

Another problem is that some CCS design concepts take several hours to ramp up or tamp down, so a CCS plant would provide mostly baseload supply and limited load following. In many areas wind and nuclear power have saturated the off-peak grid market, rendering the value of off-peak electricity nearly free. CCS fuel costs would be just as high during off-peak hours as during peak hours, but the value of the energy produced would be far lower than the value of the coal burned, even with carbon credits.

Recent studies project the average cost of CO_2 emissions abatement from large-scale CCS plants will be \$50/t-CO_2, or an additional cost of \$40/MWhr [*43*]. For retrofitting of old plants, the average of projected costs is 20% higher [*43*]. These costs will sharply limit deployment of CCS, as even without CCS coal is no longer competitive with wind energy in good wind regions.

The world's first CCS system of pilot-plant size (at \$76M) began operating in October 2009 in New Haven, West Virginia, on a 20 MW_E portion (slipstream) of the Mountaineer 1300 MW_E plant. The CCS capacity is expected to be scaled up by an order of magnitude to handle 2 Mt-CO_2/yr, or about 20% of the plant's CO_2, for an additional \$700M [*45*]. Globally, the most advanced spending targets for CCS are in the U.S., where about \$3.4B may be spent over the next several years on additional demonstration plants [*46*]. Assuming 20% savings from the learning curve, the expected public funding plus matching contributions from industry may be sufficient to build a dozen more 2 Mt-CO_2/yr CCS systems over the next five years. If so, this could lead to 26 Mt-CO_2/yr from coal emissions being sequestered in 2014. Note that the model assumed here is retrofitting 2 Mt-CO_2/yr CCS systems onto large plants that are emitting about 8-12 Mt-CO_2/yr, as this level of CCS is much more plausible than 60-90% sequestration from all perspectives – power loss, increased fuel requirements, risks, and financing.

The CO_2 market for enhanced oil recovery (**EOR**) in Texas alone could exceed the above addition to CO_2 supply in the US by nearly a factor of two [*44*], so it seems unlikely there would be much sequestration into other "reservoirs". An undesired side effect of EOR is that only about half of the CO_2 injected is still sequestered 15 years later, and most is back in the atmosphere after 30 years [*44*]. If 24 plants similar to that mentioned above are in operation in 2020 (an estimate that greatly exceeds another recent projection [*46*]), total CCS abatement then will be 70 Mt-CO_2/year. However, much of this sequestration could be temporary, with only a 15-year half-life.

As carbon capture technology is progressing for the EOR market, the challenge then should center on finding a productive use for the carbon, rather than simply spending the money to separate the CO_2 only to pump it into a deep reservoir. Later we will briefly introduce "WindFuels", a process that recycles CO_2 into liquid fuels. This could drive rapid scale-up and cost reduction for carbon capture technology.

4. CARBON-NEUTRAL ELECTRIC POWER.

Figure 5 shows the current contribution of energy sources to the electric grid in the US. Average grid carbon-intensity today is ~6 Mt-CO_2 per GW-yr of grid energy. In is important to appreciate that the addition of new carbon-neutral energy sources will not offset or displace other carbon-neutral energy: A new wind project in Kansas will not reduce the electricity generated by other wind projects – it will offset the combustion of coal and natural gas. Likewise a new nuclear facility in Illinois will not displace other nuclear power, or wind power. These carbon neutral alternatives will displace the combustion of coal, natural gas, and petroleum products. The fossil-sourced electricity in America has an average carbon intensity of 840 t-CO_2/GWh, and this is the rate that we credit the carbon-neutral grid options for CO_2 abatement.

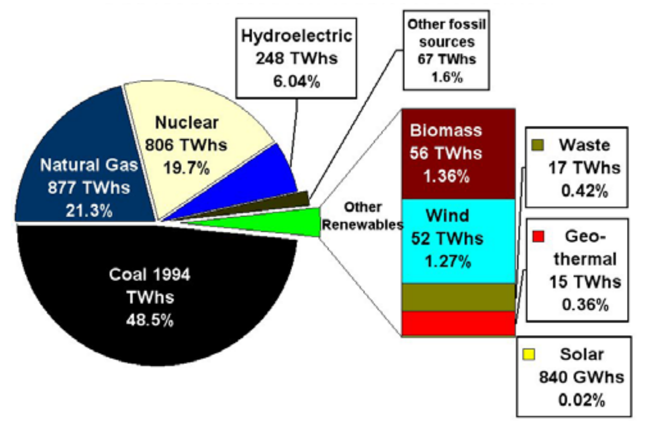

Figure 5. Sources for U.S. electric generation.

4.1 WOOD CO-FIRING.

The European Union has made a strong commitment to increased co-firing of wood pellets as one component of reducing CO_2 emissions by 20% by 2020. There are growing voices for a similar commitment to increased co-firing in the US, since it would be more beneficial than making CE from woody feedstocks [*14, 16*]. There is preliminary evidence of a synergistic benefit from co-firing a small percentage of woody biomass with coal. Co-firing 5-20% biomass leads to reduced corrosion from the more stable alkali-aluminosilicates in the ash compared to standard coal fly ash.

There are currently about 10,000,000 hectares (several Gt) of dead pine forests in North America (killed by the mountain pine beetle) providing a semi-infinite supply of free wood. This epidemic is expected to double or triple over the next five years [*47*]. Most of these ruined forests will be consumed by increasing forest fires [*23, 47*]. A massive effort to co-fire this dead wood in coal-fired plants could be the cheapest option available to reduce CO_2 emissions over the next decade. The total CO_2 abatement potential is over 1.5 Gt-CO_2.

European coal consumption is currently 1 Gt/yr, about the same as in the U.S. The energy content of wood pellets averages about 40% less than in typical European coals. In late 2009, Europe was importing about 1.5 Mt/yr of wood pellets [*48*]. They would need to increase their imports of wood pellets 180-fold to replace 20% of their coal usage. Increased wood co-firing is the easiest way to quickly reduce carbon emissions in areas where the utilization of additional wind power is difficult.

Global bulk soft-sawlog prices in the first quarter of 2008 averaged ~\$90/m^3 (\$180/t), or about \$10/GJ [*49*]. Since then, the price of sawlogs has dropped dramatically in the US because of the housing crash. Mixed sawlogs in Texas were down to only \$18.13/t in June 2009, and pulpwood was only \$5.43/t [*50*]. The extremely low regional prices for sawlogs and pulpwood have led to some unrealistic expectations for future prices of energy wood [*51*]. The mean global wholesale price of wood pellets in early 2009 was still \$200/t, or about \$11/GJ, and the wholesale price in Europe was 140€/t [*22*]. Wood pellets have typically been about three times as expensive per unit energy as coal, though both have varied widely [*4, 22, 23*].

Pellet production in the US doubled in 2008 from 1 Mt/yr to 2 Mt/yr. A 40%/yr growth rate appears likely for the next six years in the US, reaching about 16 Mt/yr in 2015. Wood pellets comprise about 70% of total traded energy wood, and the explosive growth expected in this market will begin soaking up the cheap excess energy wood and sawdust except in remote regions. Pellet prices seem likely to reach $400/t by 2015 – mostly from the combination of rising oil prices and the loss of vast dead pine forests to wild fires. Such pellet prices would not normally make sense for power producers ($230/MWhr for 38% efficiency power plant). However, this price will be driven by carbon reduction mandates and tens of millions of consumers choosing pellet stoves over oil.

Some analysts have projected a diminishing demand for wood for the paper industry. However, the global demand for paper has continued to grow. For instance: over the last decade China's demand increase surpassed the contraction of U.S. and European demand, as did their imports for paper products [*52*].

The amount of global wood usage reported by the UNECE timber data is 1.1 Gt/yr [*49*]. Other than wood pellets (about 8 Mt in 2007 and 10 Mt in 2008 [*22*]), this does not track much that is used in domestic heating and cooking, The total global sawdust available for pelletizing is about 50 Mt/yr [*49*]. Total wood usage – estimated to be about 2 Gt/yr – could probably be increased sustainably by 0.8 Gt/yr (total) over the next 40 years. If all of that growth potential were used for wood pellets, it would be sufficient to replace about 7% of current global coal usage (~6.5 Gt/yr). However, nothing close to this level of co-firing is likely, as other timber usage will clearly continue to grow over this time.

A realistic growth projection for energy wood may be 30%/yr from 2008-2014, bringing the total to about 70 Mt/yr in 2014. A 20%/yr growth beyond that would put traded energy wood at 210 Mt/yr in 2020.

The CO_2 abatement of wood co-firing is less than what some have expected. The energy density of dry wood is about 35% less than the global mean of the displaced coals. There are losses associated with wood harvesting (4%), drying (1%), conditioning (1%), pelletizing (~2%), and increased transport (compared to coal), which total ~10%. Moreover, harvesting of wood leads to less carbon being sequestered in the soils, as noted earlier. Assuming a typical native soil carbon content of 40 t/ha [*24*], a sustainable harvest rate of 7 t/ha/yr, and a 25% reduction in soil carbon over a 30-yr period, a soil-carbon debt of 5% should be assigned to the harvested wood. The combination of these effects implies a tonne of wood displaces the CO_2 produced by 0.55 t of coal (typically 70% C), or 1.4 t-CO_2.

Co-firing 210 Mt/yr (or 6.8 t/s) of wood containing 16.5 GJ/t generates 110 GW_T of thermal power. Assuming 38% mean power-plant efficiency (which is possible by 2020), the mean wood power generated would be about 42 GW_E. This would provide a total abatement of 290 Mt-CO_2/yr, or 270 Mt-CO_2/yr above the current co-firing abatement.

4.2 NUCLEAR.

A comprehensive cost study appeared in June 2009 [*53*], estimating the cost of new nuclear power to be between $120-$200/MWh. This contrasted with MIT's update on its own projected cost of $84/MWh [*54*], which it published in May 2009. Several more comprehensive reports were released in November 2009 [*55, 56*]. However, the most recent and relevant data point for assessing the cost of new nuclear power is the bid for two new Vogtle 1100 MW reactors in Burke Georgia. The U.S. government recently guaranteed 8.33 billion dollars in loans towards this 14 billion dollar, 2.2 GW bid [*57, 58*]. This implies a capital cost of $6.36/W. However, when contractors are required to shoulder the risks, recent price quotes for new nuclear plants have climbed to over $10/W [*59*]. This discrepancy is due to the unfortunate fact that all recent nuclear power plant construction has seen delays ranging from 20-38 months and cost overruns ranging from 20%-350% [*55, 56*]. Giving Georgia Power the benefit of the doubt, we'll assume only a 30% cost overrun for a final capital cost of $8.3/W.

Assuming $8.3/W, typical current O&M costs of $15/MWhr, fuel cost of $10/MWh (projected average cost over the next decade), a 40-year lifetime, capacity factor of 85%, and a 7% discount rate, the LCOE for a new plant would be ~$108/MWhr. Assuming no delays, the Vogtle Unit 3 reactor may come on line in 2016. It would then be the first new reactor in the U.S. in 30 years.

The mean concentration in uranium ores mined in the late 1970's was over 5%. Today it is under 2% U, but it is expected to drop to about 0.1% in 30 years [*60-62*]. We expect the price of uranium to be over $1000/kg by 2030, and we expect enrichment costs to be higher by then as well. This would add ~$30/MWhr to the price of uranium shown in Table 1 for 2015 ($10/MWh). By 2016, it should be clear that fuel costs of nuclear will be much higher than historically seen. Moreover, the cost of the competition for base-load energy in the U.S. and other regions with good wind resources will be much less than has been expected, as shown later in the discussion of wind.

Global nuclear energy has been slowly declining for the past seven years and is now at 370 GW, about 4% below the peak of 2002. A recent study projects that enough aging nuclear plants will be decommissioned during the next 15 years that new plants coming online will still not achieve the peak nuclear energy reached in 2002 [*63*]. The IEA 2006 reference projection, on the other hand, predicts a net of 20 GW will be added by 2020 [*1*]. The recent commitments by most countries to greater emissions reductions suggest net additions by 2020 could be twice that amount. Much faster growth (about 14 GW/yr) was maintained between 1970 and 1987, but fast net growth now seems highly unlikely, as (1) budgets are severely constrained, (2) the LCOE in many cases will not be supported by baseload demand, (3) there is limited public acceptance of nuclear, (4) aging plants could be decommissioned at a mean rate of 16 GW/yr over the next 15 years [*63*], and (5) there is a severe international shortage of nuclear engineers. An increase in nuclear power of 40 GW (our estimate) would yield additional CO_2 abatement of 250 Mt-CO_2/yr in 2020.

4.3a. PHOTOVOLTAIC SOLAR (PV).

Large PV farms achieve a global average capacity factor of 15%, and rooftop PV achieves about 13%. Local insolation has a large influence on the capacity factor of any individual installation, so there is a very wide disparity between PV capacity factors seen in the American Southwest and those in Germany. Future growth in PV is expected to be predominately in arid regions (especially near cities where peak grid rates are very high), and the average capacity factor of PV should gradually improve. By 2020, the mean capacity factor might be as high as 17%.

PV supplied ~0.03% of grid energy in America in 2008 [*64, 65*]. The latest studies indicate mean installed costs dropped 4.7% during 2008 and a similar drop is expected for 2009 [*65*]. Mean installed costs in the US for large commercial installations before incentives in late 2009 were $6.7/W [*65*]. Assuming a 30 year lifetime with 1%/yr output degradation, capacity factor of 18%, 7% discount rate, and O&M costs of $10/MWhr, the LCOE before incentives would be just over $400/MWhr. After-tax incentives reduced costs to the purchaser by over 40% in 2008; but incentives have been rapidly decreasing, and that trend will continue [*65*].

Cumulatively, about 20 GW_P of PV was installed globally by the end of 2009. PV experienced 50%/yr growth from 2004-2008. However, recent projections are for a 26% growth from 2009 to 2010 in terms of panel MW of sales, even as panel prices plummet from the severe glut in production capacity [*66, 67*]. One of the few recently announced large projects in the US – Nellis Air Force Base, CA – would build PV at the rate of 80 MW_P /yr over the next three years. Most other utility-scale projects are less than one-tenth this size [*66*]. Half of solar PV companies active in mid 2009 are expected to fail before the end of 2010 [*67*], and half of those that remain may fail before prices return to a level that allows profitability by late-2012. At that point, global installed PV capacity is likely to be about 38 GW_P

[*66*]. New capacity could then be being added at the rate of 8 GW_P /yr. With investors and most governments soured on PV because of its poor competitiveness, a likely mean growth rate from 2013-2020 might be 12%/yr. This would lead to 85 GW_P in 2020 and an additional abatement of 84 Mt-CO_2/yr.

4.3b. CONCENTRATED SOLAR POWER (CSP).

Nevada Solar One was completed in mid-2007 at \$3.7/W_{PE} (\$ per peak electrical power output) with a 22% capacity factor [*68*]. O&M costs for this 65 MW_{PE} plant are about \$45/MWhr [*69, 70*]. Ignoring subsidies and inflation, this would result in an LCOE of \$198/MWhr for a 30-yr lifetime at a 7% discount rate. A recent large project announcement (Lockheed-Starwood, 290 MW_P, trough type, \$1.5B) came in at \$5.2/W_P [*71*]. This will include some storage so its capacity factor will be higher, though the amount is unclear. A 553 MW CSP project in Mojave Solar Park is expected to supply 1388 GWhr/yr (capacity factor of 28.5%), cost \$2B, and be operational in 2011 [*72*]. A project at Fort Irwin (500 MW_P of CSP plus PV, but mostly CSP at 23% capacity factor) is expected to cost about \$2B and be operational in 2015 [*73*]. Plans for a series of up to six 242 MW_{PE} trough plants with 3.5 hours of storage using molten-salt storage were recently announced by Solar Millennium and Solar Trust [*74*], but cost and performance information on these designs is not self consistent. The project that seems most certain is the Brightsource 392 MW Ivanpah CSP facility [*75*]. After modifying the plant design to accommodate habitat concerns, this project received loan guarantees from the DOE for \$1.37B [*76*]. Project cost information could not be found, but the federal government will not guarantee more than 80% of the capital cost of the plant, so the costs cannot be less than \$4.36/W. The Ivanpah plant is designed for dry cooling, so O&M costs should be much lower than that seen for the much smaller Nevada Solar One.

The above discussion of active CSP projects in the U.S. is not exhaustive, but most other large projects announced in 2007-2008 have been cancelled. In early 2008, global CSP additions were predicted to be as large as 1.5 GW_{PE} /yr by 2010, but they were nearly frozen globally in 2008-2009 [*77*]. The mean global build rate over the next five years now appears likely to be ~500 MW_{PE} /yr. Current global installed CSP is about 500 MW_{PE}, and it is on a path to about 3 GW_{PE} in 2015.

The mean U.S. residential electricity price in late-2009 was \$110/MWhr, and the mean cost of production from coal was only about \$60/MWhr. Clearly, CSP still faces tough competition in most settings. Therefore, a growth rate beyond 2015 of 25%/yr is probably a best-case scenario. At that rate, there would be 9 GW_{PE} operating in 2020.

The average capacity factor of CSP operating in 2015 will be about 26%, and it may be 33% by 2020. Thus, the expected 9 GW_{PE} of CSP in 2020 would produce 26 TWhs – for an increased abatement of 21 Mt-CO_2 /yr.

4.4a. CONVENTIONAL GEOTHERMAL POWER.

A recently announced 22 MW project, at one of the best natural sites available (Neal Hot Springs, OR), will cost \$106M, and it is expected to be operational in 2011 [*78*]. Another recent data point comes from the \$63M, 25 MW plant in Morelia, Michoacan state, Mexico [*79*]. This amounts to \$2.5/W in one of the world's best sites in a country with very cheap labor. (Sites of this quality are rare, so such costs will not be typical.)

Global capacity additions over the past three years have averaged about 270 MW/yr (mostly in Iceland and Indonesia), bringing the current global installed base to 10.5 GW [*1, 80*]. As long as prime sites remain available in regions with base-load demand, the economics of geothermal in those sites will be quite attractive. Hence, with public support, it might be reasonable to project a 25% annual growth rate in *build rate*. A 25%/yr growth in global *build rate* would amount to ~2.5 GW/yr in 2020, with a cumulative addition of 12 GW by then. The problem with this projection is that Iceland is now bankrupt. The total build rate in the US and other countries capable of sustaining strong growth has been only about 80 MW/yr. Hence, a more plausible projection is for a cumulative addition of 3.5 GW by 2020. The total geothermal then installed globally in 2020 would be ~14 GW. At 85% capacity factor (the current mean), the additional CO_2 abatement would be about 22 Mt-CO_2 /yr in 2020.

4.4b. ENHANCED GEOTHERMAL SYSTEMS (EGS).

A major EGS study published in 2006 projected near-term LCOE from mid-grade EGS sites to be \$240/MWhr [*81*], but the costs of drilling tripled from 2004 to 2008 [*82*]. The single known investor-supported EGS project has recently been put on hold [*83*]. Clearly, EGS projections based on drilling costs from 2004 are fanciful. Our projections (using current drilling costs and allowing for a typical performance loss due to "thermal drawdown" of the site) estimate the LCOE for EGS from mid-grade sites to be \$380-\$610/MWh. EGS would often be competing with much cheaper wind, nuclear, or CSP. Thus, it's hard to imagine EGS growing to more than 250 MW of power by 2020. At that level, its CO_2 abatement would be 1.5 Mt-CO_2 /yr.

4.4c. GEOTHERMAL HEAT PUMPS.

One area where geothermal energy could make a larger impact is in geothermal heat pumps. Geothermal heat pumps use groundwater or water flowing in a loop through the ground for low-grade heat exchange rather than using outside air. This allows a reduction in energy required to heat and/or cool a house or business. As these units have become more cost competitive, the industry has seen rapid growth. In 2004, there were an estimated 1 million geothermal heat pumps worldwide [*84*]. Between 2004 and 2007, the number of units sold/year nearly doubled, and in 2007 the industry grew 35% [*85*]. The energy savings from geothermal heat pumps can pay back the initial costs in 2-10 years (depending on location and energy prices). Recent incentives and higher energy costs are likely to result in continued strong growth through 2020. Industry advocates claim that current geothermal heat pump installations are eliminating 3 Mt-CO_2/year [*86*]. Assuming 22%/year average increase in installed geo-heat pumps, the total CO_2 abatement by 2020 could be 27 t-CO_2 /yr.

5. DISTRACTIONS – GEOENGINEERING, FUSION, CONSTRUCTION MATERIALS, AND STCC.

There has been considerable hype about the possibility of reducing the GHG emissions associated with construction materials. However, no one has yet proposed a viable method of substantially reducing the CO_2 release associated with production of construction-grade cements and concretes. Most suggestions – such as those by Calera [*87*] – actually would lead to increased GHG emissions [*88*].

Suggesting switching to bamboo-based flooring [*1*] when we currently have enough standing dead wood in the U.S. to supply the construction industry for decades makes no sense. Greater use of glass could increase rather than decrease the carbon footprint of building construction, as this could require increased use of steel – which has much higher embodied carbon than wood or concrete.

A recent article in Nature says of ocean fertilization, "It's time to move on" [*89*]. The other leading proposals for geoengineering (other than aforestation in tropical and temperate zones) have also been soundly discounted [*90*]. A good example is CO_2 mineralization in olivines and serpentines. The rates of carbonate formation in finely powered silicates at normal atmospheric conditions require hundreds of millennia to absorb significant amounts of CO_2. Even in super-heated, high-pressure carbonic acid, the rates are five orders of magnitude less than needed for a practical process [*90, 91*].

Another large distraction has been thermonuclear fusion, which has no chance of becoming energy positive and competitive within the next few centuries [*92-94*], as shown most clearly in the recent study by Cellier [*92*]. Unfortunately, plasma physicists have been very well connected politically for the past three decades, and scaling back this sink-hole may take many more decades [*92*].

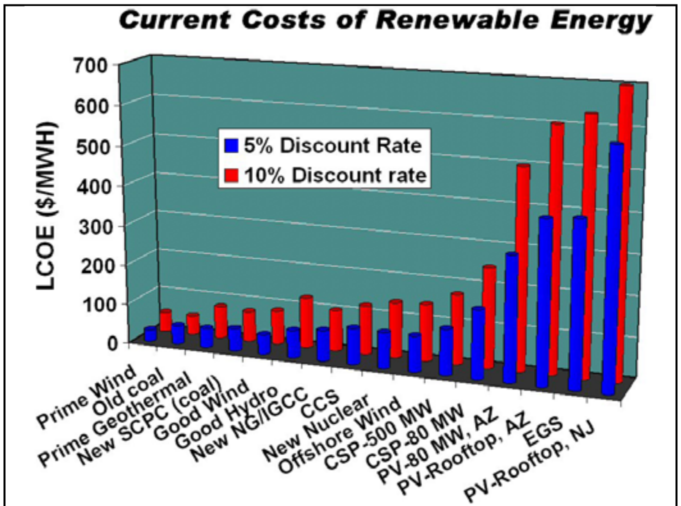

Figure 6. Depicts the LCOEs calculated in Table 1.

There has been growing interest for the past decade in exploring solar-driven thermochemical conversion (**STCC**) [*95-98*] because the solar resource is larger and more widely distributed than the wind resource. Extrapolations from available published studies [*69, 95, 99*] indicate solar thermal energy costs alone would exceed $800/MWhr at 1200 K and would double for each 100 K increase beyond 1200 K [*113*]. All STCC experiments thus far have suffered from a combination of serious practical deficiencies: (1) very short lifetime (sometimes less than 2 hours before efficiency drops in half); (2) low conversion efficiency (generally in the 0.1-2% range); (3) extremely high costs (over $30/$W_T$, where W_T is the thermal power in the receiver); and (4) severe challenges in scale-up (thermal or stress gradients that scale with size, batch-mode operation, use of precious-metal catalysts, solid reactants or solid products, impractically high optical precision, etc.). A thermo-chemical system that achieves 4% system efficiency, lasts a few days, and costs $50/$W_T$ is fiv*e orders of magnitude away from being practical.*

6. GREATER IMPACTS

6.1 ENERGY EFFICIENCY AND CONSERVATION

Energy efficiency will remain the most cost effective means of reducing our society's GHG emissions for the next decade. However, we will not spend much additional time here on energy efficiency (early, we discussed two related topics, SCPC power plants and geothermal heat pumps), as this subject has been sufficiently treated elsewhere [*1, 4, 6, 14*]. Many efficiency improvements can be achieved on any level and can fit any budget, and many efficiency options have reasonably short payback periods. Conservation steps can often be taken to reduce energy demands at negligible expense – such as car-pooling, less strenuous climate control, and telecommuting.

We estimate that at least 1.2 TWhs/yr energy demand will be reduced globally by 2020 (offsetting at least 1000 Mt CO_2/yr) by use of compact fluorescent lamps, better insulation, better windows, low-power appliances, natural lighting, and simple conservation steps [*1*].

6.2 HYDROPOWER

Hydropower is by far the largest source of carbon-neutral electricity in the world. Global installed capacity was ~777 GW in 2006 [*100*], generating one-sixth of the total electric power produced worldwide, and it has been growing rapidly. China alone added 53 GW between 2007 and 2008, and another 76 GW is already under construction [*101*]. These projects often serve multiple functions, providing irrigation, grid stability, and other needs. .

The material cost for dam construction is trivial compared to that of labor and land inundation. In poorer nations, the value of labor is quite low, and the costs associated with inundating large portions of land is manageable. For instance, the recently completed Three Gorges Dam had a construction cost of only ~$27.5B for a project that produces ~100 TWhs/yr. However, the project inundated 400 square miles of fertile land and required the relocation of 1.24 million people, including large towns and small cities. The construction involved 20,000-40,000 workers laboring in round-the-clock shifts for 12 years [*102*].

In the industrialized world, that same project would cost ~$125B assuming the following for first-world costs: (1) eminent domain: ~$60,000/displaced person; (2) Labor: $40/hour; (3) Land: $300,000/km^3; (4) Roller Compacted Concrete (RCC): $180/m^3; (5) Steel: $680/t; (6) Earth movement: $25/ m^3; and (7) Turbine costs of $75/kW. Though this estimate is rough and ideal dam sites have mostly been exploited in the first world; this figure will be used here for comparison with the other alternatives. Assuming a 50-year lifetime, a capital discount rate of 7.5%, and an O&M cost of $1/MWh; the LCOE for a project of that scope in the first world would be ~$91/MWh.

Available data on projects currently under construction and in advanced planning stages [*101*] suggest that 250 GW of new hydropower could come online (mostly in industrializing nations) by 2020. This could yield 800 Mt-CO_2 /yr additional abatement by 2020. It seems unlikely that hydropower will scale up beyond 1200 GW global capacity, as there would then be few sites in which a dam could be competitively built.

6.3 WIND.

It has often not been easy to accurately determine the costs of wind projects, as the contract bids are not always reported. However, the American Recovery and Reinvestment Act (**ARRA**) allows groups to forego the ITC or PTC and instead receive 30% of their investment in renewable energy projects in a direct cash subsidy [*103*]. For those

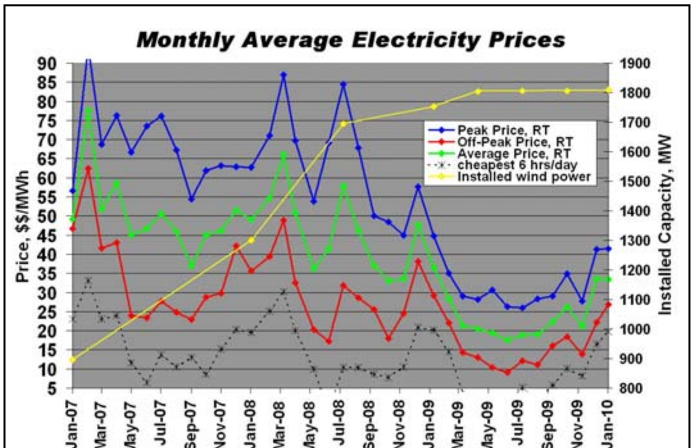

Figure 7. The recent rapid drop in off-peak real-time grid prices in areas of high wind penetration has been astounding. As the price dropped, new construction has ceased.

projects that have chosen the cash subsidy, it is now a simple matter to calculate their exact project costs. The mean cost for US wind projects completed in the first 9 months of 2009 appears to be $1.85/W [*104-107*]. The cheapest of these projects is the Hay Canyon Wind Farm – a 101 MW project in Oregon that received 47 million dollars from the DOE, implying an initial cost of $1.55/W ($1.09/W after the ARRA reimbursement). The largest wind farm that took the cash subsidy was the Pyron Wind Farm – a massive Texas 249 MW project at a cost of $1.63/W. The most expensive power is the Stetson wind farm in Maine – a 57 MW array of wind turbines along a mountain ridgeline that cost $2.36/W [*102*]. These projects were bid on and began construction in the period of 2007-2008. Since then, turbine costs have dropped by

18% over the prior year as nationwide demand plummeted in the wake of the economic recession [*108*].

Large wind farms are being bid today at \$780/kW (installed) by Chinese firms in some parts of the world [*109*]. Typical O&M costs for wind energy are now \$1/MWhr [*110*]. Even at \$1600/kW$_P$, capacity factor of 33%, 7% discount rate, 40-year lifetime, and O&M costs of \$1/MWhr, the LCOE (before incentives) is \$45/MWhr. **Figure 6** shows graphically the attractiveness of wind compared to alternatives. Note that our calculations assume only a 40-yr lifetime, but relevant data suggest a 60-yr lifetime may soon be typical. For example, about 96% of the large turbines installed by Bonus in California in the mid-1980s are still operating with very low maintenance.

Globally, wind energy has sustained a 22%/yr growth rate for the past 15 years. Yet most recent studies conclude the growth rate going forward will be much less because of increased difficulties in dealing with the excess off-peak energy [*1, 4, 13*]. Large investments will be made in upgrading transmission lines, which will help wind continue to grow. Massive deployment of energy storage could also help by transferring the excess energy from off peak markets to markets that have strong demand. However, most traditional energy storage options are not economically viable for progressing the growth in wind [*111*]. Fortunately, there is a novel solution, as we discuss in the next section.

The current global installed wind base is 140 GW$_P$. If the 22%/yr growth rate of the past 15 years were maintained, that would rise to 1.2 TW$_P$ in 2020. With a mean capacity factor of 33%, wind would then be abating over 2900 Mt-CO_2 /yr. Such a growth rate is very optimistic without much more rapid grid expansion and energy storage development than recent trends suggest. However, with expanded transmission or energy storage solutions, wind could resume its meteoric growth. We anticipate 900 GW$_P$ installed wind base in 2020. If so, the increase in CO_2 abatement by 2020 would be 1900 Mt-CO_2 /yr.

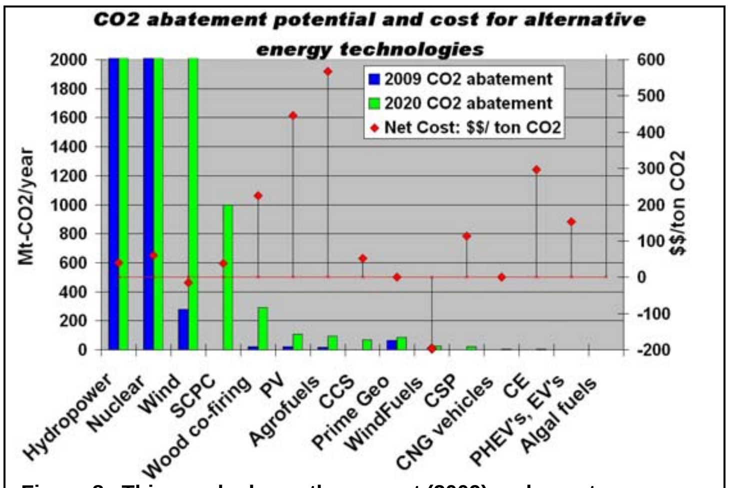

Figure 8. This graph shows the current (2009) and near term potential (2020) CO_2 abatement for several energy technologies. The projected cost to abate 1 ton of CO_2 is plotted in red and shown on the right axis for each alternative.

6.4 WINDFUELS.

The continued need for liquid transportation fuels is undeniable and again beginning to be recognized as likely to be urgent within a few years [*112, 113*]. But as was discussed, biofuels will not (and should not) scale-up to meet this need. However, it is possible to synthesize all types of fuels (gasoline, diesel, jet fuel, alcohols, and other chemicals) at high efficiency (50-62%) from CO_2, H_2O, and off-peak wind energy [*114, 115*]. Off-peak wind energy in areas of high wind penetration averaged \$16.4/MWhr in 2009, as seen in **Figure 7,** and the lowest cost 6 hours of the day averaged only \$7.1/MWh throughout 2009 [*116, 117*]. At such prices, these low-carbon "Windfuels" could compete when oil is as low as \$45/bbl. By offering an off-peak demand that can respond instantly to load variation, Windfuels will allow the continued growth of wind and nuclear energy. For this reason, we expect that wind and nuclear will eventually provide most of the baseload energy demands throughout most of the world. Coal would then be used for peaking and load following, and its average capacity factor should fall consistently over the next 4 decades.

The excess off-peak energy used by WindFuels should be over 92% carbon neutral. These fuels would also contain a small carbon footprint from the extra energy used to separate and purify the CO_2, giving a total carbon intensity of ~12 t-CO_2/TJ. This is under one-eighth that of tar-sands fuels and would offset 14 Mt-CO_2 /Bgal.

This technology is still in the early development phase, but unlike biofuels and EV's, there will be strong economic incentives and no real obstacles to rapid scale-up. There is sufficient wind energy potential and point-source CO_2 (over 4 Gt/yr, from coal plants, cement factories, biofuels plants, steel mills, etc.) in the U.S. alone to synthesize half of the world's transport fuel demand, with enough remaining wind energy potential to supply all its other energy needs. The input potential is similarly favorable in Russia, Canada, China, the northwestern coast of Africa, the U.K, Australia, Brazil, and some other countries [*118*].

We expect that with rapid R&D investment, the first commercial-scale WindFuels plant (~50 MW) could be operational by 2015. In the expected fuels market of 2015 [*112, 113*], we expect the profit from a WindFuels plant to pay back the capital investment in only 18 months. This economic incentive could raise sufficient funds to construct a 250 MW plant and 20 to 100 smaller (50 MW) plants worldwide by 2018. The build rate could increase by 30%/year thereafter for several decades.

By the end of 2020, we expect global Windfuels production at the rate of 2 Bgal/yr. The CO_2 abatement for this would be 25 Mt-CO_2 /yr. However, no other transport fuel alternative comes close in growth potential beyond 2020. By 2045, the potential WindFuels CO_2 abatement could be 15 Gt-CO_2/yr.

7. SUMMARY AND CONCLUSION.

Figure 8 summarizes our assessment of current (2009) and mid-term potential (2020) CO_2 abatements for the alternatives discussed above. The red points in Figure 8 show the net cost for industry to pursue that technology in comparison to the cheaper, more carbon-intensive alternatives.

Tables 2 & 3 summarize our calculations for the cost of CO_2 abatement. It is clear that the most significant increase in CO_2 abatement from the energy alternatives (other than possibly hydropower in the third world) will be from wind (1900 Mt), SCPC coal (1000 Mt), wood (270 Mt), and nuclear (250 Mt). The next largest impact comes from PV (84 Mt), but this CO_2 abatement comes at a very high cost. Agrofuels show the sixth greatest potential (75 Mt) – but this may be optimistic and represent close to an ultimate resource potential. The sum of all the rest (not including geo-heat pumps and efficiency) is just 147 Mt-CO_2 /yr. The growth in CO_2 emissions, especially in the developing world, seems likely to exceed the total increase in CO_2 abatement by about 5 Gt-CO_2 /yr over the coming decade.

It is clear that other than wind and hydropower, renewables will have a small effect in the next decade on CO_2 emissions abatement. However, when coupled with recent major advances in storing excess off-peak wind energy in standard liquid transportation fuels, the long-range potential of wind is seen to be enormous. Wind has already begun to reduce coal usage in the U.S. and in Europe. Wind and Windfuels could replace 70% of ***both*** coal and oil usage globally over the next 40 years. Carbon sequestration then would not be needed.

Table 2. Cost (and profit) of CO_2 mitigation via alternative transport fuels in 2016.					
Resource	Cost of fuel $/gal	Market price $/gal	Net cost (gain) for alternative $/gge	gge for 1 ton CO_2 abatement	Net cost (gain) for CO_2 mitigation $/ton$CO_2$
WindFuels**	1.80	4.25	(+ 2.45)	80	(196)
CNG vehicles*	4.25 (gge)	4.25 (gge)	0.00	166	0
PHEV's, EV's*	5.10 (gge)	4.25 (gge)	0.85	180	153
Cellulosic Ethanol	5.50	3.40	2.80	106	297
Agrofuels	4.60	3.40	1.60	355	568
Algal oil	60	4.25	56	-250	Infinite

* The expected premium for the capital costs for this is amortized into the fuel over a 10-year period. ** The sale of co-produced oxygen is subtracted from the price of the fuels.

Table 3. Costs (or profit) of grid-CO_2 mitigation in 2016.					
Resource	LCOE $/MWh 7.5% rate	Cost of offset power* $/MWh	Net cost (gain) $/MWh	CO_2 abate. MWh/ t-CO_2	Cost (gain) for CO_2 abate. $/ton
Wind *average*	54	66	(12)	1.25	(15)
Prime geothermal	66	66	0	1.25	0
Replacing old coal with SCPC	66	48	18	2.09	38
Good Hydropower	98	66	32	1.25	40
CCS *coal*	107	66	41	1.25	51
Nuclear *fission*	115	66	49	1.25	61
Natural Gas	91	66	25	2.90	72
CSP	157	66	91	1.25	114
Wood co-firing	230	73	157	1.43	225
PV solar *CA rooftop*	508	151	357	1.25	446
EGS	520	66	554	1.25	568

*Replacing old coal with SCPC is assumed to offset old inefficient coal power. Wood co-firing is expected to offset coal power in Europe. PV solar is expected to compete with residential electricity in California.

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