Biofuels Trajectory to Success: The innovation ecosystem at work

By Vinod Khosla

What's up?

Under what set of circumstances would the worlds best known academic plant biologist, molecular biologist and DNA sequencing expert, with the help of a malaria drug researcher, start working together on a new biofuels start-up?

Can you imagine a Silicon Valley executive from Apple moving to Denver, running a company in the back of a pipe fitting shop founded by an aging wildcatter up to his ears in debt?

Would Silicon Valley investors travel to Australia and make their largest investment to date in a solar technology used to heat up water for a pulverized coal plant? Invest in a start up company in New Zealand that is converting waste gas from steel mills into ethanol?

How about Amyris, a company funded to the tune of $40M from the Gates Foundation to develop artemisinin - now transforming itself into a next generation biofuels company? Or Gevo, a company originally formed casually in response to "you can't do that with synthetic biology yet" to taking on BP-Dupont in the race to commercialize biobutanol?

Chris Somerville, head of the Carnegie Institute and Professor of Plant Genetics at Stanford, is considered the world's foremost authority in plant biology. George Church, Professor at Harvard Medical School, is widely considered the leading academic scientist in the country having been at the forefront of DNA sequencing, bioinformatics, systems biology and synthetic biology. Jay Keasling is a professor at Berkeley and is considered a leader in synthetic biology; he was named the "Scientist of the year" in 2006 by Discover Magazine. They have come together to start LS9, a company making petroleum from the fermentation of cellulosic feedstocks. LS9 is using synthetic biology to move pathways from plants into bacterial cells from which hydrocarbons will be extracted using modified refinery technology. Plant Genetics + Synthetic Biology + Chemical Engineering = LS9 = Renewable Petroleum - now that is a reaction worth noting.

Khosla Ventures visited an entrepreneur who worked out of a pipe fitting shop in an industrial park in Denver. Leveraging his pipe fitting business with debt, he had developed an anaerobic gasification process to convert biomass into ethanol. His office was so small that during our initial visit, half of the meeting attendees were standing against the wall; and trust us, you were better off using the bathroom at Denver International. However, there was something very compelling about the entrepreneur and despite the shabby exterior, the technology passed muster with many third party engineering firms who rated it highly. For our own satisfaction, we had experts from leading universities, national labs, and companies look at the technology on our behalf. The response was unanimous: this was a potentially exciting technology. More impressive was the number of the reviewers who were willing to join the company. For example, Dr. Arie Geertsema, who had run commercial R&D at Sasol and at that time was Director of the Center for Advanced Energy Research at University of Kentucky. After reviewing this technology, he moved his family and took over as the Chief Technical Officer of the company. Then came Mitch Mandich, former head of sales at Apple, who gave up a job running a $700M public software company to take the CEO job here. Seemed like a no-brainer, give up a job guaranteeing millions of dollar per year income in an industry he knew well to buy a house in Colorado and run a one man company operating out of a pipe fitting shop in Denver. Less than eighteen months later, Range Fuels has started construction of the first commercial cellulosic ethanol facility. Phase I should be operation in late 2008 or early 2009

One of the hottest new fields in biotechnology today is synthetic biology. This is the art of applying engineering principles to biology, something that was impossible until the advent of automated DNA sequencing and advanced DNA synthesis technologies. It opened up avenues far beyond traditional genetic engineering. Amyris, founded by Jay Keasling, received a large grant to develop a biobased drug for malaria treatment in sub-Saharan Africa. Heeding the advice of herd mentality VC's Amyris came to us with a plan on how to apply their technology to pharmaceuticals. A company founded by four chemical engineers working on drugs made no sense and we asked them about the possibility of applying the technology to biofuels. After evaluating specialty chemicals and a variety of biofuels, Amyris is now well down the path of introducing a proprietary diesel molecule made by fermentation of cellulosic feedstocks and has hired a world class CEO from BP.

Gevo is a company we co-founded with Professor Frances Arnold, a pioneer in DNA shuffling technologies, after a casual conversation at a talk on synthetic biology. She claimed that two graduate students working for a year or two could make the process of designing bugs that convert methane to methanol conversion economic using these techniques. A year into the company, the team decided to take some of the initial innovations and apply it towards a whole new problem: making butanol from sugars and cellulose. Only in a start up can you make such a dramatic change without skipping a beat, replacing the team, and wasting resources.

We know that yeast has evolved over billions of generations to survive at high ethanol concentrations making it the bug of choice for beer, sugar, starch and now cellulose based ethanol. Who would have thought a small research outfit in New Zealand would have identified a bug that was multiple-fold more ethanol tolerant and rather than sugars as a feedstock uses carbon monoxide gas from the flue gases from steel mills. They estimate that fifty billion gallons of ethanol can be made annually from the waste of steel mills. Clean up the liability of steel mill exhaust to produce biofuels that produce cleaner, cheaper transportation fuels. A true bioecosystem at work! In addition, the same technology could be used to further improve the Range Fuels process to produce ethanol from syngas.

Coskata is another one of our investments. A number of researchers looked at the syngas production process that Range had but thought they could improve upon the syngas to ethanol catalytic conversion process by replacing it with bugs that convert syngas to ethanol. Coskata was born as a science experiment with a license to technology from the University of Oklahoma, bold new ideas, a few million in seed funding and a few great researchers.

While a lot of our work is on increasing the supply of biofuels, we also have investments aiming to reduce demand for transportation fuels. Transonic was founded by Mike Cheiky, an inventor/entrepreneur outside the traditional automotive mold – he has expertise in batteries, fuel cells and computer architecture. Utilizing this array of skills, Transonic is using proprietary fuel injection technology to increase the efficiency of gasoline engines by a 100% – providing an immediate boost to fuel economy, and potentially providing a sharp reduction in consumption. This would single-handedly change the discussion around CAFE ("corporate average fuel economy" standards which is an automotive fuel efficiency measure) standards in this country and lead to reducing oil consumption in nearly half if successful!

Several chemical engineers and researchers from Europe with more than twenty-five years of experience developing catalysts and processes for petroleum refining formed a company to develop a process to add biomass directly into the fluid catalytic cracking (FCC) unit of an oil refinery. A few experiments and the idea of converting biomass to a biocrude appropriate as a replacement for fossil crude, and Kior was born.

Elsewhere, an oilman with an equipment manufacturing plant develops a new method for pre-treating biomass that opens up totally new options for converting the biomass into fuels and chemicals. A chemical engineer with a company that has built numerous plants around the world for the production of specialty chemicals develops a highly efficient process to convert biomass into diesel fuel directly. Every day, we receive another pleasant surprise as long as we keep an open mind to possibilities. Even feedstock sources are being innovated, much like the example of producing fifty billion gallons of ethanol form the flue gases of steel mills. What about flue gases from oil refineries? Or producing algae or other feedstocks in open water ponds or even in the ocean? There are other stories, the vast majority of which we are probably not even aware of. But we keep looking. Our war on oil demands we find replacements for gasoline, for diesel, for aviation fuel and other products made from oil.

So what is going on here? It is a classic example of the innovation ecosystem at work, solving large problems by harnessing the power of ideas fueled by entrepreneurial energy of our scientists, technologists, and entrepreneurs. Nothing signals opportunity than some of the best and brightest people working on solving a problem. And nothing results in more progress than people with very different backgrounds, from very different industries coming together and challenging traditional industry assumptions about what is possible and what is impossible! This is exactly where we find ourselves today in the renewables industry. Many impossible things are becoming possible. We have seen many debates on the internet on why we don't have enough land, why the energy balance won't work, why we cannot scale fast enough, and on and on and on. They are generally right if one takes a traditional approach, but these new ideas and approaches are attempting to bypass these limitations, find clever workarounds or alternative paths. Some will work and some will fail, but we suspect the world will be well on its way to solving its oil dependency crisis within a decade if not within five years.

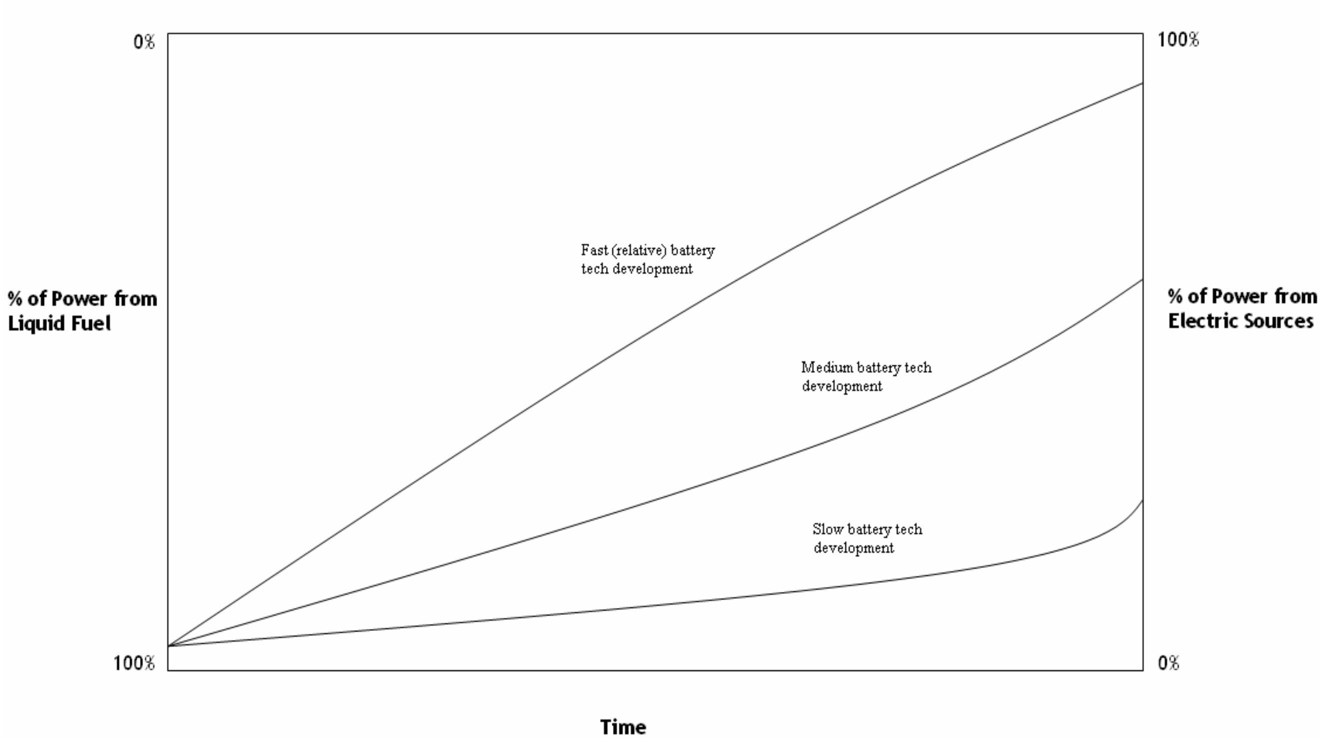
We have multiple investments and believe that all of them can be successful. The fuels market is comprised of multiple markets: gasoline, diesel, jet fuel, home heating oil and other specialty markets. There will be winners in each segment. Even within a segment like gasoline, the market is large enough that any biofuels producer who achieves a cost target of $1.25 per gallon or so will be very successful. This is akin to each oil well and region having a different cost of oil production but as long as their cost is below the market cost of oil they can find a market!

Priming the Innovation Engine

Can we change fuels, feeds, and automobiles in one go? The goal, as we see it, is a liquid fuel for the internal combustions engines - the hundreds of millions of engines that are there or likely to be put on the roads in the next decade or two.

After a new engine penetrates into the bulk of new cars sold (and it can only do that when it is extremely cost effective), it still takes 15 years to replace the fleet of cars on the road to this new engine given the life expectancy of the average car. Can we replace our internal combustion engines with something else? Can we make all cars electric? What is the best way to introduce new paradigms like electric cars and efficiency? To introduce new fuels? Shouldn't we take an opportunity to allow the innovation ecosystem to work in engine development? There are a variety of approaches possible.

Any engine drive-train or power-train additions that costs thousands per car like hybrids and plug-in hybrids, will cost trillions (additional cost over just simple fleet replacement over 15 years) when applied to the total US automotive fleet (over 230 million cars, plus additional trucks and other vehicles). We believe such engines must pay back in fuel savings when translated to additional monthly car payments to make substantial headway (achieve 50% penetration of new car sales) into the market beyond the early adopters – the typical monthly car payment plus fuel costs should decline after including the cost of fueling the vehicles; otherwise, it is unlikely to make a near term difference (in the next decade or two). Cars can be made as flex fuel vehicles (FFV's) capable of running on either gasoline or ethanol for a marginal cost of only $35 per car! Since biofuel cars are virtually no additional cost it is entirely possible that we can achieve a significant FFV fleet in 15 years, especially since the US automakers have committed to make 50% of our cars FFV's by 2012. Improving efficiency on internal combustion engines is also possible and innovative startups are trying to achieve 30-50-100% efficiency improvements. Some will surely succeed, even if traditional thinking big auto approaches say it is not possible on a cost effective basis. The innovation ecosystem has proven to us enough possibilities and technical approaches for us to fund multiple engine ventures. Transonic expects to increase efficiency a 100% for incremental costs of hundreds of dollars (versus thousands of dollars for the 25% efficiency improvements hybrids afford us). Ecomotors' (one of our investments) uniquely designed engine can generate significantly more "bang for the buck" than conventional engines, and will be used to power serial plug-in hybrids. Tula Technologies is developing a chip that can help improve the efficiency of engines. Elsewhere, better hybrid drivetrains and batteries are being developed. Given the widespread attention being paid to this area, it seems likely new car efficiency will reach 50-75 miles per gallon (fleet averages) within the next 25 years – reducing oil use projections more than 50%. Fortunately FFV's are completely compatible with most of this technical progress, as well as improvements in hybrids and plug-in hybrids too. In the next decade, the principal automotive engine is likely to be the standard internal combustion (ICE) or diesel engines with increasing efficiencies, slightly adapted to FFV use. As hybrid and plug-in electric technology continues to penetrate the market, it will further reduce the demand for liquid fuels (see the chart below)– in the long run, rather than competing, **the two could serve to complement each other, resulting in vehicles that use improved (and cheaper) battery technology coupled with a more efficient liquid-fueled engines. Eventually, plug-ins may even reach a dominant role, but that is unlikely to happen worldwide in the next decade or two.**



Within 25-50 years, we may well see a transition to an all electric propulsion fleet, depending on the relative technical progress on battery, fuel and engine efficiency technology. Biofuels are likely to be a significant source of our "non-oil" transportation energy needs in the next two decades. The extent to which we use batteries is going to be a function of the cost of oil, the cost of biofuels, and the scalability of the biofuels technologies. An extended version of this discussion of hybrids is available in our “Hybrids” Paper.

On the topic of hybrids, we are optimistic about serial hybrids, which can help improve ICE engine efficiency substantially (we discuss hybrids in more detail in our Hybrids white paper). Essentially, parallel hybrids have an internal combustion engine (ICE) and an electric motor (powered by a battery), both of which are connected to the transmission and both of which can thus power the car. A serial hybrid, in contrast, uses the ICE to power a generator, which can either charge the battery or power an electric motor. Given the reasonable premise that change in our electric grid (with a 50 year plant timeline) is likely to be slower and more gradual than the adoption of biofuels through FFV cars, plug-in hybrids are less likely to offer a material impact in carbon emissions but ICE engine efficiency improvements using serial hybrids are very complementary to biofuels use. The cost of hybrids and hence their ability to penetrate 50-80% of the billion or so cars likely to be produced in the next 15+ years worldwide remains a major concern and source of some skepticism to us that hybrids can materially affect carbon emissions. The additional cost of a hybrid drivetrain is likely to stay in the thousands of dollars per car.

As biofuels penetration grows, we will see continued evolution of today’s engines as they are optimized for biofuels. Today we run ethanol in a gasoline optimized engine at a compression ratio of about nine, which fails to take advantage of ethanol’s ability to run at much higher compression ratios. Engines designed for ethanol-first will operate at compression ratios of around sixteen, and will get far more mileage than their energy content would indicate, probably even more miles per gallon on ethanol than today’s gasoline engines. Substantial possibilities exist for even better engines, and companies like Transonic (and others) are working on just that. The innovation ecosystem is at work in engines as well - we expect to see improvements in engine fuel efficiency complement those of the yield, cost, land efficiency and performance improvements of biofuels. We hope to see a happy nexus of reduced consumption (through better engine efficiency), lighter-weight cars (and other vehicle improvements,) and a dramatic expansion of our capability to produce more fuels at lower costs at increasing land efficiencies over time. In this paper, we will illustrate the impact of the innovation ecosystem on the role of biofuels in our transportation system.

As discussed, it appears likely that the bulk of our transportation energy needs (for the next 25 years) will be met by liquid fuels for internal combustion engines. For alternative liquid fuels to be a viable option, feedstocks have to be available that can scale and have declining costs with scale. Cellulosic biomass meets both these requirements, as does waste (agricultural, municipal sewage, animal waste etc). For an alternative fuel to succeed, the feedstock and its collection, aggregation, transportation and processing must be such that the end product is competitive with gasoline. Corn ethanol has done a great job of getting us stated in the US. Sugarcane has proven the viability of the Brazilian model. However, the only feedstock that can produce 100-billion plus gallons of biofuels in the US alone is cellulosic materials. (Waste materials can add materially to the supply). In the short term, the engines are relatively fixed because of the fifteen year replacement cycle. The cost effective alternatives are likely to be improved combustion engines and flex-fuel engines, the fuels are liquid fuels and the only scalable feedstocks are likely to be cellulosic biomass. We will see slow and gradual penetration of hybrid engines into the new car sales mix. But it is unlikely to change oil consumption materially in the next decade or two. What trajectories are we seeing today for cellulosic feedstocks and what is it likely to lead to? What will be the process of this evolution?

Fuel Feedstocks and Yields:

One of the primary points of contention with biofuels has been the availability and scalability of biofuel feedstocks (our paper - Where Will Biomass Comes From covers this in more detail). We think these concerns are significantly overstated, and we outline a summary of our views on feedstocks here.

How will production work? While there are many approaches to feedstock production, making a material impact in replacing gasoline will require major feedstocks that can collectively produce more than a hundred billion gallons in the US and preferably more than 150 billion gallons to replace gasoline. For a biofuel to be a sustainable, long-term solution to our transportation fuel needs, yields of at least 2,000 (hopefully up to 3,000) gallons per acre are required. A competitive feedstock cost based on current conversion efficiencies (which are subject to improvement), delivered to the factory, has to be below $50/ton of dry biomass (plus or minus 25% depending upon feedstock type) to compete with $50/barrel oil (which we are unlikely to see again without significant reduction in demand for oil). As such, we limit (in our estimates) potential incremental land using feedstocks to crops that yield over 10 tons/acre in the mid-term – effectively, “energy crops” and forest waste.

Now to the numbers. How much biomass can we get to convert to biofuels without subsuming other uses for land and biomass? More than enough! There are four principal sources of biomass and biofuels we consider (1) energy crops on agricultural land and timberlands using crop rotation schemes that improve traditional row crop agriculture AND recover previously degraded lands (2) winter cover crops grown on current annual crop lands using the land during the winter season when it is generally dormant (while improving land ecology) (3) excess forest product that is currently unused (about 226 million tons according to the US Department of Energy), and (4) organic municipal waste, industrial waste and municipal sewage. The table below is our projection of the most likely scenario – using about 70% of excess forest waste, 50% of annual crop land for winter cover crops, and about 15M acres of dedicated crop land in order to meet most light-vehicle needs in 2030.

Scenario 1

	KV Cellulosic Ethanol Production Estimates	Waste Ethanol Production Estimates	Ethanol Yield (Gals/Ton)	Total Biomass Needed	Winter Cover Crop Acres	Winter Cover Crop Yield	Forest Excess Biomass	Forest Biomass Yield	Biomass needed from dedicated cropland	Expected Yield (Tons/ac)	Acres needed at projected yield	Acres needed at 75% of projected yield	Acres needed at 50% of projected yield
	(Gallons - Billions)	(Gallons - Billions)	(best tech)	(Tons - Millions)	(Acres - Millions)	(tons/ac)	(Tons - Millions)	(tons/ac)	(Tons - millions)	(Tons - millions)	(Tons - millions)	(Tons - millions)	(Tons - millions)
2015	5.0	0.0	102.3	48.9	4.1	3.4	20.8	10.9	14.0	10.9	1.3	1.7	2.6
2020	30.0	3.0	107.5	251.1	42.9	3.8	68.3	15.4	19.4	15.4	1.3	1.7	2.5
2025	87.6	8.0	110.0	724.1	142.5	4.2	125.5	20.5	0.0	20.5	0.0	0.0	0.0
2030	150.0	15.0	110.0	1227.3	158.5	4.6	158.0	24.5	334.2	24.5	13.6	18.2	27.3

How Do We Get There?

Total Biomass	=	Winter Cover Crops:	Forest Excess Waste:	Dedicated Crop Land:
2015: 49M tons	=	14M tons	21M tons	14M tons
2020: 251M tons	=	163M tons	68M tons	19M tons
2025: 724M tons	=	599M tons	126M tons	0M tons
2030: 1227M tons	=	735M tons	158M tons	334M tons

2030 - How Much Land Do We Need?

	24 t/ac	18 t/ac	12 t/ac
Displaced Land - Due to Dedicated Energy Crops	13.6	18.2	27.3
Reclaimed Land - based on 2008 corn ethanol production, assuming 70% land recovery	-15.5	-15.5	-15.5
Net Land Use (Excluding Winter Cover Crops, Forest Excess Waste)	**-1.9M acres**	**2.7M acres**	**11.8M acres**

How do we get to the numbers above (all the scenarios and our assumptions are listed in Appendix A)? While science and technology will continue to be an important factor in increasing yields, the usage of improved agronomy practices is a major factor. There are a few areas that offer significant potential – (i) crop rotation (we have proposed a 10 x 10 year energy and row crop rotation), (ii) the usage of polyculture plantations (polycultures have significant environmental benefits and are more efficient), (iii) perennials as energy crops (less need to replant, and they play a significant role in restoring soil resources), and (iv) better agronomic practices such as no-till farming and non-irrigated crop growth. We address all four issues in our “Where Will Biomass Come From” white paper. While all four areas have yet to be studied extensively, we believe that there is immense potential here.

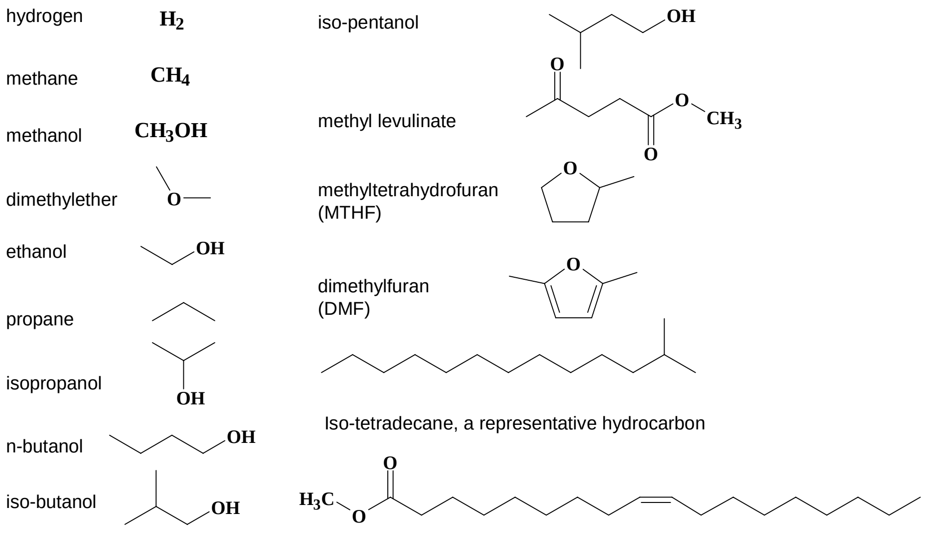
While our most critical assumption here is one of yields (in tons of biomass per acre), both public and private research tends to confirm our assumptions – many reported examples and data points of biomass yields speak to the reasonableness of our estimates of between 18-24 tons per acre by 2030 and 110 gallons per ton of biofuel (in fact, we have seen unreleased research that suggests 150 gallons per acre is feasible – long before 2030!). Moreover, cellulosic ethanol can be derived from a wide variety of would be crops, allowing flexibility for local conditions around the world.

In conclusion, we are confident that available and developmental feedstocks will allow cellulosic biofuels to meet our transportation fuel needs by 2030, and perhaps sooner. Moreover, this can be accomplished in ways that limit our land use footprint, increase the viability and sustainability of our soil resources, and sharply contribute to reductions in carbon emissions. Some may call it a pipe dream – we think the innovation ecosystem will prove it to be reality. It is important to note, as the many scenario studies show, that biomass can be produced with good carbon reduction practices or done poorly with net adverse carbon emissions implications if we start growing energy crops on cut down rain forests. We must follow good sustainability and carbon emission standards in developing biomass crop practices. It is imperative that policy and legislation dis-allow poor biofuel and biomass production practices.

Fuels – Chemistries and Characteristics

What will the future biofuels be? Fuel chemistry has started with ethanol as an alternative fuel and may possibly evolve to better chemistries. We may even get different fuels for different applications. A different synthetic fuel may power airplanes than one used for cars. Butanol is a possibility as an automotive fuel because of its higher energy density and lower vapor pressure and fewer gasoline blending constraints; the broad range of possibilities include cellulosic gasoline, cellulosic biodiesel, cellulosic “biocrude”, and many more. The potential for customized chemistries means that we can remove an hydroxyl (OH) group here, add an hydrogen (H) there, create a longer or shorter carbon chain to optimize the fuel for the intended purpose. For example, instead of plant oils, microbial fatty acid metabolism can be modified to make diesel from cellulose, with improved properties such as viscosity and cloud-point. Some of these innovations in the production of existing fuels and the development of new fuels are shown in the figure below. Here we address some of the approaches to fuel chemistries we are aware of – from the conventional to the unconventional, the probable to the crazy. While not all of these will prove viable, some will prove more beneficial than gasoline and diesel.

Some members of the biofuels ecosystem



Iso-tetradecane, a representative hydrocarbon

Methyl oleate, a fatty acid methyl ester (FAME), representative biodiesel molecule

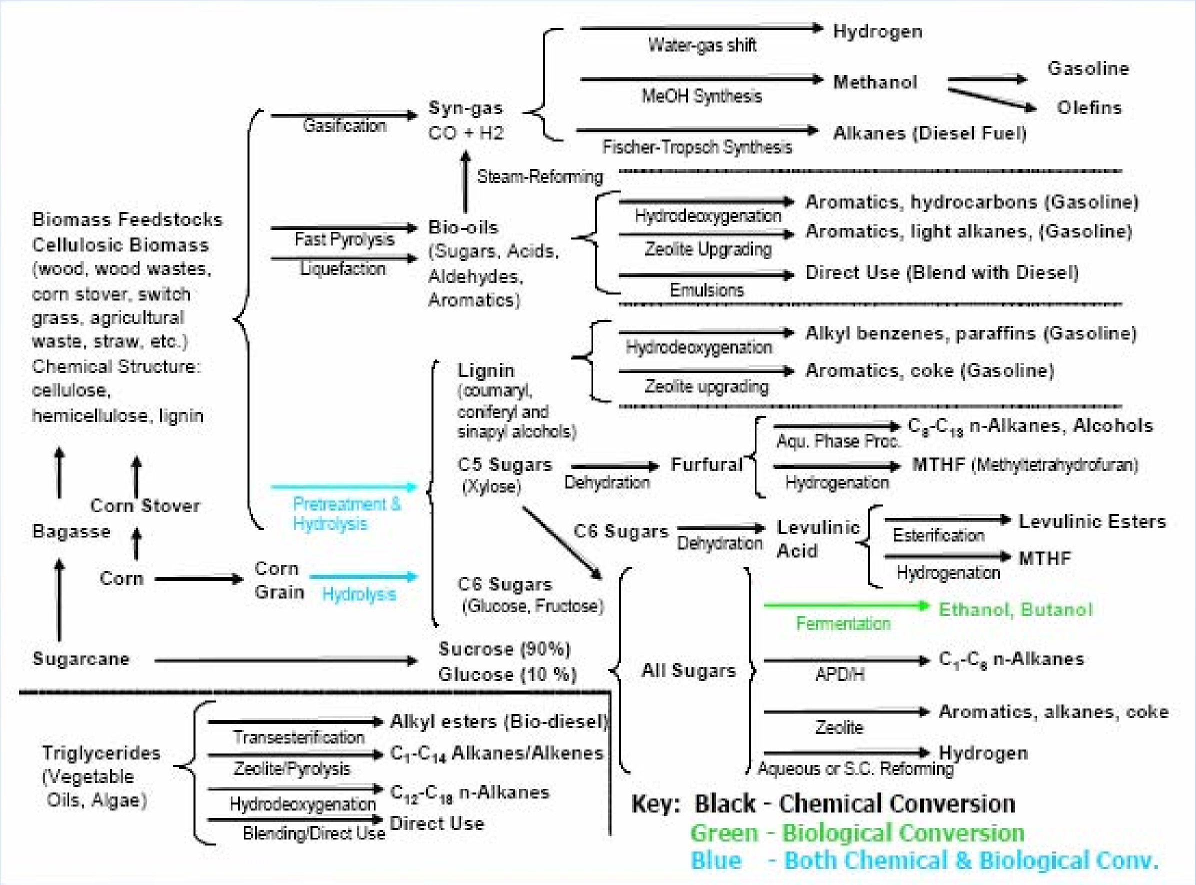
Corn/Sugarcane/Starch-based ethanol: The conventional approach to ethanol is the traditional dry mill ethanol process used primarily in the corn belt of the United States. The ethanol is then shipped to population centers. In “destination” corn dry mills the corn is shipped to a population center where it is needed for animal feed so that the ethanol does not need to be transported as far. Distillers grain (DGS) needed for animal feed is the protein content of the corn is produced as a byproduct of converting the starch in corn into ethanol. A step beyond the traditional dry mill is corn fractionation which separates oil from the DGS. Fractionation is a way to get additional value from the corn. The simplest version of fractionation is to remove the corn oil before fermentation (the oil is a valuable co-product). Many other variations have been developed including removing the corn oil from DGS after production of ethanol. Companies with fractionation processes include Renessen (joint ventures of Cargill/Monsanto), and Poet. Lower oil content in the DGS allows for higher levels of an animals feed being DGS, thus increasing the demand for DGS and reducing the demand for corn and utilizing the corn better. Other variants abound – sugarcane to ethanol is a relatively straightforward process practiced most often in Brazil.

Away from the specific processes, it must be recognized that corn ethanol’s greatest value is as a “stepping stone” and transition-point to cellulosic ethanol, butanol, and even more attractive cellulosic fuels. . Corn ethanol is not the long-term future fuel that will replace all of our oil needs – its lack of scalability means it is unlikely that we will produce more than 15 billion gallons and most ethanol beyond 2015 or so will be cellulosic as corn ethanol will not be able to compete. Even if corn yields continue to increase (Monsanto’s projections suggest that the advent of biotechnology combined with molecular breeding will result in yields of around 300 bushels per acre from about 150 today), corn ethanol is limited in its ability to scale far beyond the 15 billion gallon threshold. However, it offers the first step in the trajectory from 500 gallons per acre to 3,000 gallons of fuel per acre – it mitigates many of the early, technological and capital risks associated with cellulosic ethanol, and helps to develop the infrastructure necessary for cellulosic ethanol, as well as other biofuels. We need to hone our production technologies, get the flex-fuel automobiles (FFV's – it costs just $35 to make a new car capable of handling both E85 and gasoline) in place and the infrastructure for pumping, storing, and transporting ethanol implemented – in effect priming the pump. Incidentally, most such infrastructure will also apply to many future liquid fuels like butanol that are being considered. Equally importantly, ethanol is compatible and complementary to other petroleum use reduction technologies like hybrids and plug-in electric hybrid cars. Even though it is not the long-term solution, corn ethanol is a key fuel that is critical to getting alternatives started to petroleum. As the cellulosic technologies scale over the long run, corn's limits will be self defining.

Cellulosic Ethanol:

One of the most active areas in the biofuels innovation ecosystem is the conversion of lignocellulosic biomass to ethanol. The fermentation of biomass is challenging relative to the fermentation of corn starch and sugar from sugarcane for two main reasons. First, although both starch and cellulose are polymers of glucose, it is much more difficult to hydrolyze cellulose to glucose than to hydrolyze starch. Second, unlike starch and sucrose, which are made entirely of six-carbon sugars, biomass also contains a significant amount of five carbon sugars. The yeast that is currently used for almost all ethanol production, Saccharomyces cerevisae, does not naturally use five carbon sugars. The mainstream cellulosic biofuels efforts are geared towards the conversion of cellulose to sugars and their biochemical conversions to fuels, though many other approaches are equally promising and are discussed below. The figures below[1] from Huber provide a basic overview of some of the more promising approaches.

Figure 0.4: Routes to Make a Biofuel, adapted from Huber et al. [2006].



Biochemical Conversion to Ethanol: Many different approaches are being used to address the challenge of cellulose hydrolysis. An important step is biomass pretreatment to make the cellulose accessible to further treatment. Pre-treatment approaches include the use of dilute sulfuric acid, concentrated sulfuric acid, super critical water, phosphoric acid, acetone, and ammonia (for example, Ammonia Fiber Expansion, AFEX, developed by Bruce Dale at Michigan State University). Mechanical processes have also been coupled with the chemical treatments, including size-reduction and extrusion. Some of the pre-treatment methods also result in some cellulose hydrolysis, especially the processes with concentrated acid. However, just as enzymes such as amylase are used to hydrolyze starch, many researchers and companies, such as Novozymes and Genencor, are developing cellulose enzymes to hydrolyze cellulose. Another approach is to use organisms that make their own cellulose-degrading enzymes or to engineer cellulose-degrading activities into an ethanol producing yeast. For example, as championed by its cofounder, Lee Lynd of Dartmouth, Mascoma Corp. is developing “consolidated bioprocessing” to making ethanol using organisms that both hydrolyze cellulose and ferment the resulting sugars to ethanol. One approach being developed by Mascoma is to use a natural celluloytic organisms such as Clostridium thermocellum. Another approach, being developed in collaboration between Lee Lynd and Emile van Zyl at the University of Stellenbosch in South Africa, involves engineering Saccharomyces to produce celluloytic enzymes. Mascoma’s approach comes with built-in cost advantages – a 4x lower enzyme consumption because of thermophilic microbes and lower cost because of consolidated bioprocessing (CBP), something we see as a key to producing byproducts (such as ethanol) at a $1.25 production cost. In addition to Mascoma, several other companies are exploring consolidated approaches, including SunEthanol and TMO Renewables. Organizations are also screening for cellulose using organisms and enzymes in natural ecosystems such as in the guts of ruminant animals (cows, goats, elephants) and in cellulose using insects such as termites and wood eating beetles. In fact, the Department of Energy Joint Genome Institute has recently completed sequencing the termite gut metagenome and is working on the metagenome of the Asian Longhorned beetle, a wood-eating beetle.

As mentioned above, a second challenge is that biomass contains a significant amount of five carbon sugars and the conventional ethanol yeast does not use such sugars. This was one of the first problems to be address by genetic engineering in the late 1970’s and early 1980’s. One of the first people to solve the problem was Nancy Ho, a molecular biologist in the Purdue University Laboratory of Renewable Resources Engineering (LORRE). , Nancy engineered a three enzyme pathway that enabled Saccharomyces to ferment the five-carbon sugar xylose to ethanol. Her yeast is now being used by Iogen Corporation, though we are somewhat skeptical on its feasibility without subsidies.

Another person to address this problem was Dr. Lonnie Ingram, a professor of microbiology at the University of Florida. Professor Ingram approached the problem from the completely opposite direction; instead of adding the ability to use five-carbon sugars to an ethanol producing organism, he added the ability to produce ethanol to E. coli, an organism that naturally uses a diverse range of sugars. The genes for the ethanol pathway came from Zymomonas mobilis, bacterium used to make the Mexican alcoholic beverage, pulque. He has continued to make advances in this area and his technology is the basis for the ethanol fermentation developed by Celunol, which was bought by Diversa, the combined company now called Verenium. Many other research labs around the world have engineered other approaches to fermenting C5 sugars like xylose.

Other approaches to the fermentation of five-carbon sugars are being explored. For example, at group of researchers at the National Renewable Energy Laboratory (NREL), took the opposite approach as Lonnie Ingram—they engineered the ability to use five-carbon sugars into Zymomonas. DuPont is investigating this organism for ethanol production. Tom Jeffries at the USDA Forest Products Laboratory is developing Pichia stipitis, a naturally occurring xylose-utilizing yeast (as the source of two of the genes in the Nancy Ho pathway) into an ethanol producer. Xethanol and other companies are investigating the use of this yeast. Through various screening processes, a number of additional bacteria that both ferment five and six carbon sugars and produce ethanol have been identified. Some of these bacteria have the added advantage of growing at high temperatures (60oC or higher), making ethanol recovery more economical that with Saccharomyces which prefers temperatures less than 40oC. Even the xylose isomerase work mentioned above has been revisited. In the past, this approach was unsuccessful because the focus was on xylose isomerase genes from bacteria. In the last few years a collaborative effort involving an academic group from Germany, and three groups in Holland--the Technical University in Delft, Nedalco and BIRD Engineering--found a xylose isomerase in an anaerobic fungus isolated from elephant dung and used it to successfully develop Saccharomyces cerevisiae strains that ferment xylose to ethanol. Cargill (NatureWorks division) has also successfully expressed this activity in the high temperature yeast, Kluyveromyces marxianus.

For full disclosure, Mascoma is a Khosla Ventures investment.

Gasification – In addition to the fermentation approaches detailed above, there are additional methods to produce ethanol through gasification. Instead of hydrolyzing biomass to sugars, biomass can be gasified to synthesis gas (syngas), a mixture of carbon monoxide (CO) and hydrogen (H2). The syngas can then be converted to ethanol by microbial fermentation with gas-utilizing microbes or with chemical catalysts. The chemical catalysis approach is described in *Breaking the Chemical and Engineering Barriers to Lignocellulosic Biofuels: Next Generation Hydrocarbon Biorefineries (2008).*

The best known syngas using microbe is Clostridium ljungdahlii. It normally ferments syngas to acetic acid, but strains and process conditions have been developed to favor ethanol production over acetate. Companies working in this area include BRI, Coskata, and LanzaTech (the last two are Khosla Ventures' investments). Some microbes can also use carbon monoxide alone as a feedstock for ethanol. Carbon monoxide is a waste product of industrial processes such as steel and aluminum production. In order to get the hydrogen required for ethanol production, the organisms carry out the water-gas sift reaction. Some of the CO reacts with water to give H_2 and CO_2: $CO + H_2O \rightarrow H_2 + CO_2$

Coskata has developed a process to ferment syngas to ethanol. The process involves the use of specially designed bioreactors that enable the rapid and efficient transfer of the syngas to microbes (from the genus Clostridia). The chemical equation for this reaction is $2CO + 4\ H_2$ - - > $C_2H_6O + H_2O$. The Coskata process carries two further advantages: 1) microbes do not make mixed alcohols, as they have a high selectivity for ethanol and 2) microbes are less sensitive to syngas impurities as compared to chemical catalysts. Therefore, Coskata can potentially use syngas from a variety of gasification technologies with a lesser need to clean the gas.

Elsewhere. LanzaTech also has a process for the microbial production of ethanol from gases, but with different species of microbes and a different bioreactor design than Coskata. In addition to syngas, the LanzaTech microbes can also produce ethanol from carbon monoxide, a major waste product of industrial processes such as steel and aluminum manufacture. The microbes have enzymes that enable them to obtain the hydrogen needed for the ethanol production from water via the water-gas shift reaction. The chemical equation for producing ethanol from carbon monoxide is: $6\ CO + 3\ H_20$ $- - > C_2H_6O + 4\ CO_2$. The economic potential of using a waste product (currently, steel mills pay a tipping fee to dispose of Carbon Monoxide) is enormous – LanzaTech believes it can produce 50 billion gallons of ethanol from the world's steel mills alone, in addition to syngas!

Range Fuel (a Khosla Ventures investment) uses a thermo-chemical//chemical catalysis approach for the conversion of lignocellulosic biomass to ethanol. The first step of the process is the gasification of biomass to synthesis gas (syngas), a mixture of carbon monoxide and hydrogen. The syngas is cleaned and then passed over a proprietary metal catalyst that transforms it into mixed alcohols. These alcohols are then separated and processed to maximize the yield of ethanol of a quality suitable for use in fueling vehicles. Range Fuels produces a mixture of primarily ethanol with some methanol. The have received funding from the US Department of Energy for a commercial-scale plant in Georgia to convert wood (forest slash or waste) to ethanol – and are likely to be operational in 2009. Range's technology is targeting production costs of below $1.25 per gallon in its first plant, with further reductions to come with scale. **The process should reduce carbon emissions per mile driven by 75% while reducing water use and land use by 75% (as compared to corn ethanol).**

Future Fuels

Butanol and other advanced biofuels and feedstocks: In addition to ethanol, microbial processes are being developed for other biofuels. Butanol was commercially produced by the fermentation of sugars from the 1910's through the 1980's (the last plant was shut down in South Africa in the 1980's). At that time, butanol was produced mainly as an industrial solvent. The advantageous fuel properties of butanol have resulting in several companies working on reviving the traditional process (and developing new ones). The main limitations of the traditional process are (1) the selectivity for butanol is low (a large amount of acetone, ethanol and sometimes isopropanol is also produced) and (2) the final concentration of butanol is low due to its toxicity to the organisms. Modern biological approaches are being used to address both of these limitations. Several companies are working on improving the traditional butanol producing organisms—they include Gevo, BP-DuPont, Metabolic Explorer, Green Biologics, Advanced Biofuels, and Cobalt. Several of these companies are also using synthetic biology to enable organisms such as E. coli and yeast to produce butanol.

Gevo (a Khosla Ventures investment) is using synthetic biology to develop microbial processes to convert sugars to butanol. Whereas, the conventional butanol producing organisms also produce significant quantities of acetone and ethanol, Gevo has overcome this problem by developing organisms where butanol is the primary product. In addition, they have also developed organisms that produce various versions of butanol. These next-generation biofuels will serve as replacements for petrochemicals ranging from diesel to aviation fuel.

Conversions lipids and plant oils: Classic biodiesel is most commonly produced by the reaction of vegetable oils with methanol using sodium hydroxide as the catalyst. This transesterification reaction gives a mixture of biodiesel (fatty acid methyl esters, FAME) and glycerol.

The next generation processes use improved catalysts which result in a higher purity and better quality glycerol. They also enable the use of lower quality vegetable oils such as restaurant frying oils (that contain free fatty acids). The traditional sodium hydroxide catalyst will react with the fatty acids to form soap. Research labs are also exploring the use of enzymes such as lipases as catalysts for biodiesel production.

Processes have also been developed to convert vegetable oil to fuels similar to regular diesel fuel (and thus able to take advantage of current, diesel optimized engines). These processes are similar to those used in a petroleum refinery such as hydrotreating, which involves reacting the oil with hydrogen in the presence of a catalyst. The product of such a reaction is called “green” diesel. The co-product is propane rather than the glycerol associated with biodiesel. Vegetable oils can also be treated in a petrochemical fluid catalytic cracking (FCC) unit to give a gasoline-like product called “green” gasoline. Other more promising (in our view) applications of hydrotreating and FCC are also being tried. From a business perspective we are less than optimistic about the economic competitiveness of these oil based feedstock sources or their scalability.

Algae-based fuels: As with vegetable oil, algae can be used to produce lipids that can be converted to biodiesel, green diesel or even green gasoline. GreenFuel, Solazyme, Aurora BioFuels, PetroSun and Solix Biofuels are developing processes for the growth of lipid containing algae and the conversion of the lipids to biodiesel fuel. GreenFuel is developing bioreactors to grow the algae on CO2 from coal burning power plants. In addition to biodiesel, they describe the potential to ferment the residual biomass to ethanol or digest the material to methane. LiveFuels plans to grow algae in open ponds and then to produce a “biocrude” which will not be converted to biodiesel, but rather, will be processed in an oil refinery. There is some question about the eventual economics of algae based oils but of all the feedstock alternatives to cellulosic biomass, we consider algae worthy of development. The principal environmental question is the appropriateness of genetically engineered algae in open ponds or the oceans.

Catalytic Chemical Processes: The usage of catalytic chemical processes to convert sugars and biomass to fuels is another approach. Jim Dumesic at University of Wisconsin developed a catalytic process called aqueous phase reforming to convert sugars to hydrogen and formed Virent Energy Systems to commercialize the technology. Virent has also modified the technology to produce hydrocarbons, a more promising alternative though the use of sugars remains an economic and scalability problem. Professor Dumesic also recently developed a catalytic process to convert sugars to dimethyl furan (DMF), a potentially useful new fuel. As a whole, we are optimistic about the prospect of cellulosic-feedstock based fuel products.

Processes to convert biomass to levulinic acid have been known for many years. The reaction of levulinic acid with alcohols such as methanol, ethanol or butanol, give esters that have useful properties as fuels or fuel additives. Levulinic acid can also be converted to methyltetrahydrofuran (MTHF). Mixtures of MTHF with ethanol and with pentanes (derived from petroleum), called P-Series fuels, where developed by Stephen Paul, a physics professor at Princeton.

Designer Fuels: Another interesting area is designer future fuels; we highlight two of our investments in the area. Amyris has discussed directly producing cellulosic diesel from sugars and cellulosic materials. Molecules with longer or shorter carbon chains, and increased or reduced oxygen content can be produced. Since some of these fuels will phase separate in fermentation broths, they require less energy to recover than a water soluble fuel such as ethanol. Using synthetic biology and their proprietary modular pathways, Amyris is working on a next-generation fuel that is compatible with existing automotive and distribution technologies.

The focus of LS9 is to develop microbial processes for the production of fuels that fit directly in the current petroleum infrastructure. They have used the tools of synthetic biology to produce two different classes of products based on the fatty acid metabolic pathway. The first is microbial biodiesel and the second is microbial "biocrude". The biodiesel product is the same as vegetable-oil derived biodiesel except that: (1) it is produced from sugars or biomass rather than from plant oils. Therefore, the yield per acre of LS9 biodiesel can be much higher than for traditional biodiesel. (2) Traditional biodiesel is a mixture of different molecules that depends on the plant-source. Some of these molecules cause problems, such as cloudy oil that plugs diesel engines. LS9 can design the microbe to make the biodiesel with the ideal molecular composition. The second class of product is "biocrude". LS9 has developed microbes that make long-chain hydrocarbons that can be processed at an oil refinery to enable the introduction of renewable material into petroleum products. The LS9 biodiesel and biocrude have an additional advantage in that, unlike fermentation ethanol, the products are insoluble in water and float to the top of the fermentation. Therefore, recovery of the products from the fermentation is very energy efficient.

Both Amyris and LS9 offer significant technology breakthroughs in designer fuel, and we are bullish on their prospect of competing with gasoline (and other biofuels) on a cost basis – LS9 notes that they will be cost-competitive with $50 per barrel oil, without subsidies.

Other Thermo-chemical processes: A range of thermal chemical processes are being explored and developed for the conversion of renewable resources to fuels. Here they are classified as pyrolysis, liquefaction, depolymerization/repolymerization (thermal and catalytic) and gasification. These processes are often combined with additional processing steps to modify and up-grade the products. Such processes are the subject of a recent NSF report. (NSF. 2008. *Breaking the Chemical and Engineering Barriers to Lignocellulosic Biofuels: Next Generation Hydrocarbon Biorefineries.)*

Pyrolysis processes are run at low pressures (1-5 atmospheres) in the absence of air and water (steam). The resulting bio-oils are water soluble and have a fairly high oxygen content. They have a low heating value, so they may be suitable for boiler and heating fuels, but not for transportation fuels. Companies in this area include Dynamotive and Ensyn. Companies are also working on ways to upgrade pyrolysis oils to liquid fuels. UOP describes the fractionation of the crude pyrolysis oil into a pyrolytic lignin phase and a water soluble phase. The lignin phase is hydrotreated and hydrocracked to give gasoline. The water soluble phase is reformed to produce hydrogen for the lignin processing.

Kior,(a Khosla Ventures investment) is developing technology to integrated pyrolysis with a petrochemical refinery. They are carrying out the pyrolysis in the presence of a catalysis that make the material suitable for adding directly to the fluid catalytic cracking (FCC) unit of an oil refinery. Their Biomass Catalytic Cracking (BCC) process enables Kior to convert ligoncellulosic biomass into a “biocrude” that can then be converted to transportation fuels. Kior’s proprietary advantage lies in its low-energy usage process to make the woody biomass accessible to catalysts, allowing the catalysts to convert it to a biocrude product – other thermo-chemical processes are significantly more expensive (in energy and/or chemical usage). They are targeting a $45 per barrel (or cheaper) biocrude that can compete directly with oil. We consider this approach to be a promising thermo-chemical process going forward.

Another thermal chemical process is through liquefaction. It involves the use of a solvent such as water, a catalyst and hydrogen. Shell has described a liquefaction process using water as the solvent called Hydrothermal Upgrading (HTU). An advantage of HTU over pyrolysis is that the biomass does not need to be dried (since water is added anyway). However, the reaction pressure is higher, leading to increased capital costs. The up-grading part of the process is carried out by a process similar to hydrocracking in a petrochemical refinery.

While pyrolysis and liquefaction are the primary thermal chemical processes, other thermal approaches have been developed. For example, Changing World Technologies has described a thermal conversion process called thermal depolymerization for the conversion of feedstocks such as animal fats, grease, bones and feathers to diesel fuel. Another process known as “depolymerization and catalytic synthesis” along with other variants of pyrolysis, catalysis, depolymerization and polymerization have been proposed. These processes have issues around the scalability of their feedstocks. We see the innovation ecosystem very actively at work using these technical approaches.

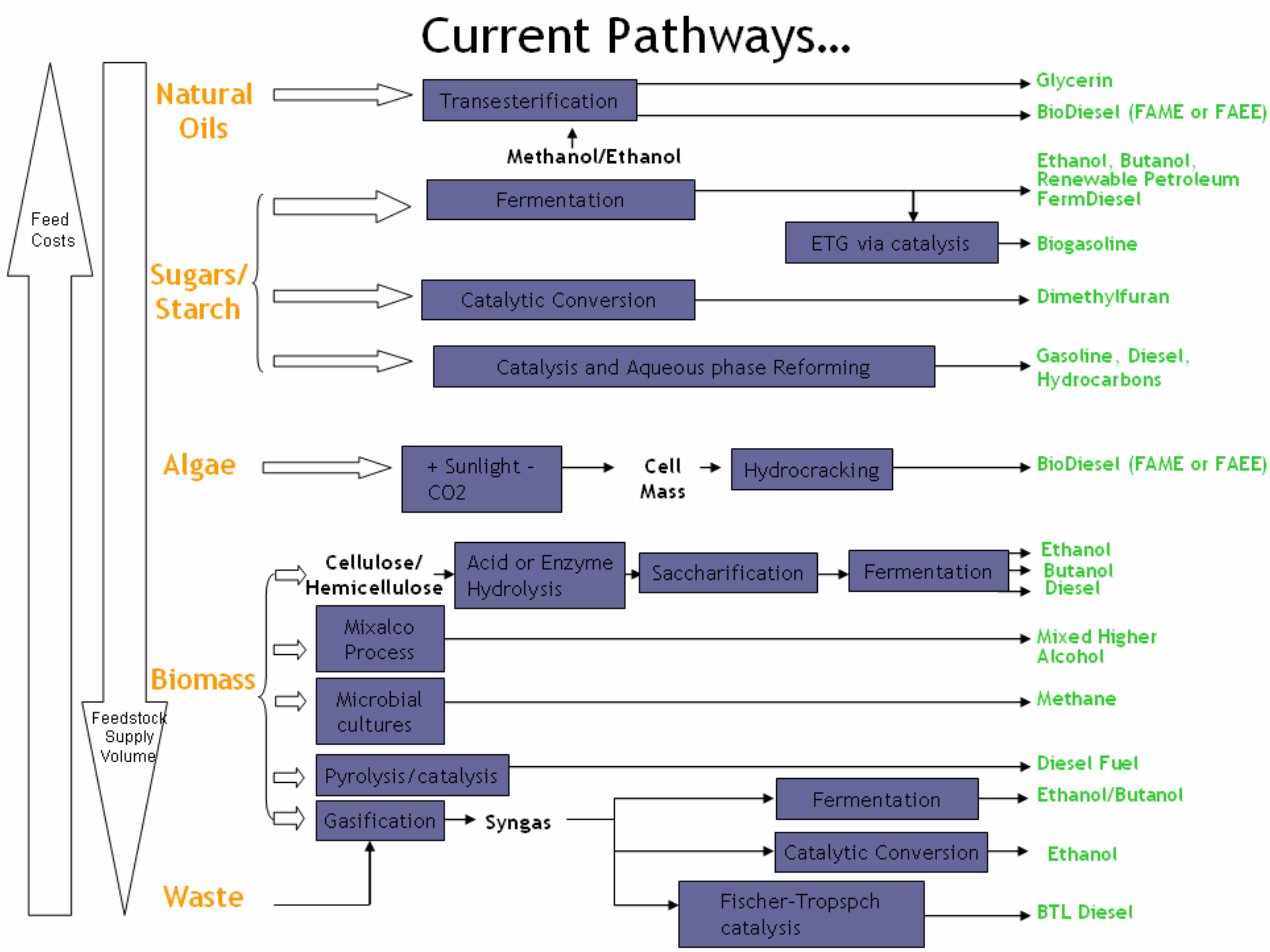
Other Gasification Approaches: We have previously described the conversion of syngas to ethanol using fermentation or chemical catalysis. However, the most well-know use of syngas is for the production of hydrocarbon fuels using Fischer-Tropsch (FT) catalysis. The non-biological processes for use of syngas are described in the Huber NSF report referenced above. This technology has been developed for the production of fuels from syngas produced from coal, primarily by Sasol in South Africa. The technology is referred to as coal-to-liquid (CTL) technology. If the syngas is derived from biomass, it is called biomass-to-liquid (BTL) technology – Choren (a German company) is working with this process to develop SunDiesel. We believe that substantial innovation is possible in the production of hydrocarbons from syngas, with cost reductions well below current levels.

Syngas can also be converted to methanol. Methanol can be used as a transportation fuel. Methanol can be converted by hydration to dimethylether, which is currently used as a diesel fuel in specially converted engines. Exxon Mobil has developed a process to converted methanol to gasoline (“MTG” process), which has the added advantage of requiring no change in engine technology for optimization. Syngas can also be converted to methane--a purely chemical route to methane as opposed to the biological anaerobic digestion process described above. In addition, syngas can be converted to dimethylether (DME), a compound that can be used a diesel fuel (but require that the engine be modified) or as a propane replacement. The key in all these approaches is to make these alternative fuels scalable and cost effective.

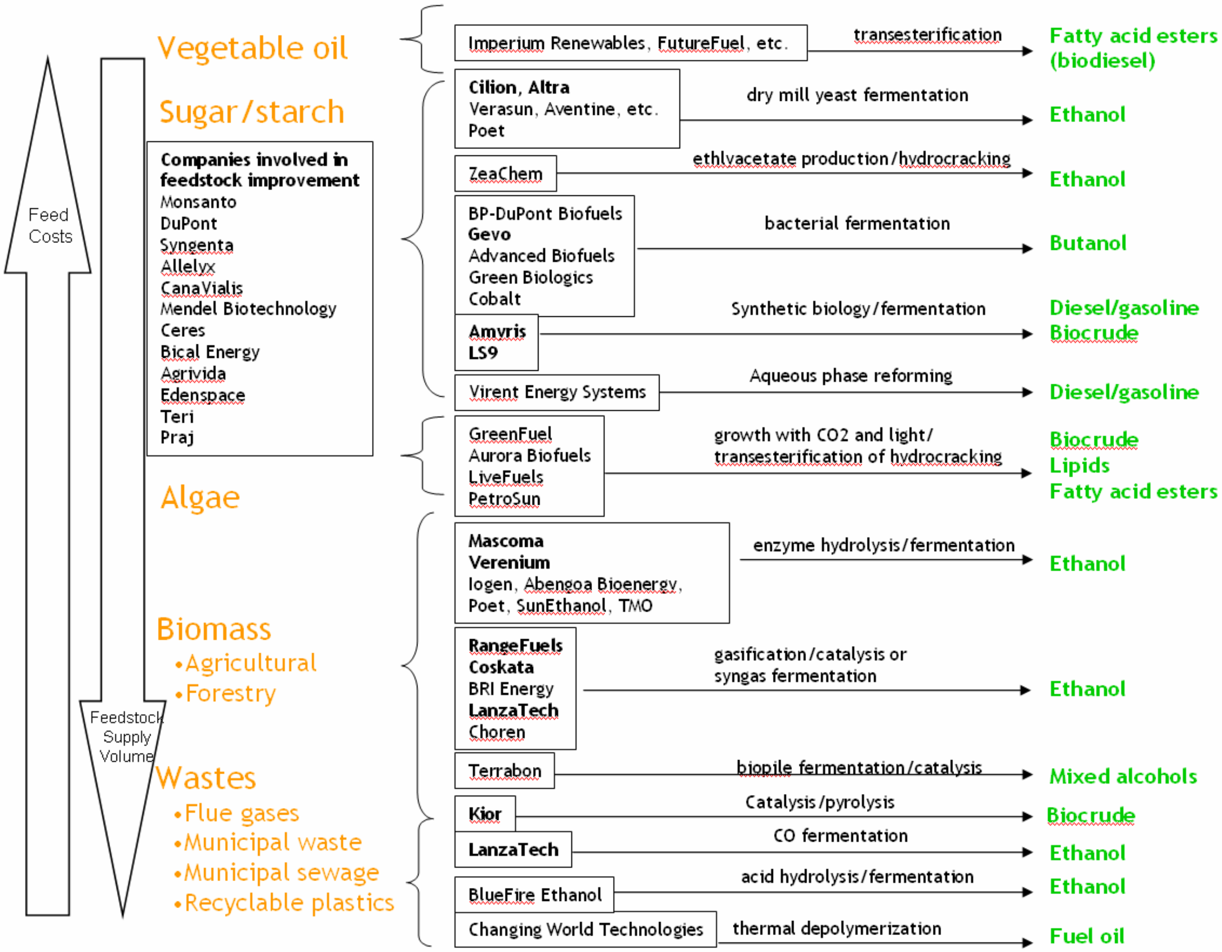
Other Compatible Hydrocarbons: C3 Biofuels, a company founded by two engineering students from MIT and a business school student from Harvard has developed a combined microbial/chemical route to propane. Sugars are fermented to butyric acid, which is then chemically decarboxylated to form propane. Mark Holtzapple, a chemical engineer at Texas A&M developed the Mixalco process in which a mixed culture of microorganisms convert biomass such as sorghum to a mixture of organic acids. The organic acids are then chemically processes to fuel consisting of a mixture of alcohols.

Two other fermentation-derived fuels also deserve mention. Mixed populations of microorganisms in landfills and agricultural waste lagoons convert carbohydrates such as cellulose to organic acids which are then converted to methane (biogas) by a process known as anaerobic digestion. There are many companies working on ways to increase the rate and robustness of this process. The other fuel is hydrogen gas; many microbes produce this as a product of carbohydrate fermentation. For example, Anaerobe Systems is exploring the use of microbes to ferment substrates such as food processing waste to hydrogen. Several companies and university research labs are investigating the use of engineered microbes to get improved yields of hydrogen from sugars. Other groups are exploring the use of engineered photosynthetic microbes to make use of light from the sun to split water into hydrogen and oxygen or to produce cellulose directly. Just about every experiment researchers can think of is being tried. Though we are less bullish about these fuels as replacements for oil, we do encourage experimentation.

The chart below highlights some of the more common pathways that we are aware of. Some of these approaches have been utilized successfully for decades (sugar fermentation in Brazil), while others are newer and more susceptible to technology risk. While feedstocks from natural oil to biomass (and waste) are viable, they do have different cost profiles: feed costs decrease as you go from oils to biomass down the chart, while the availability of feedstock supply increases.



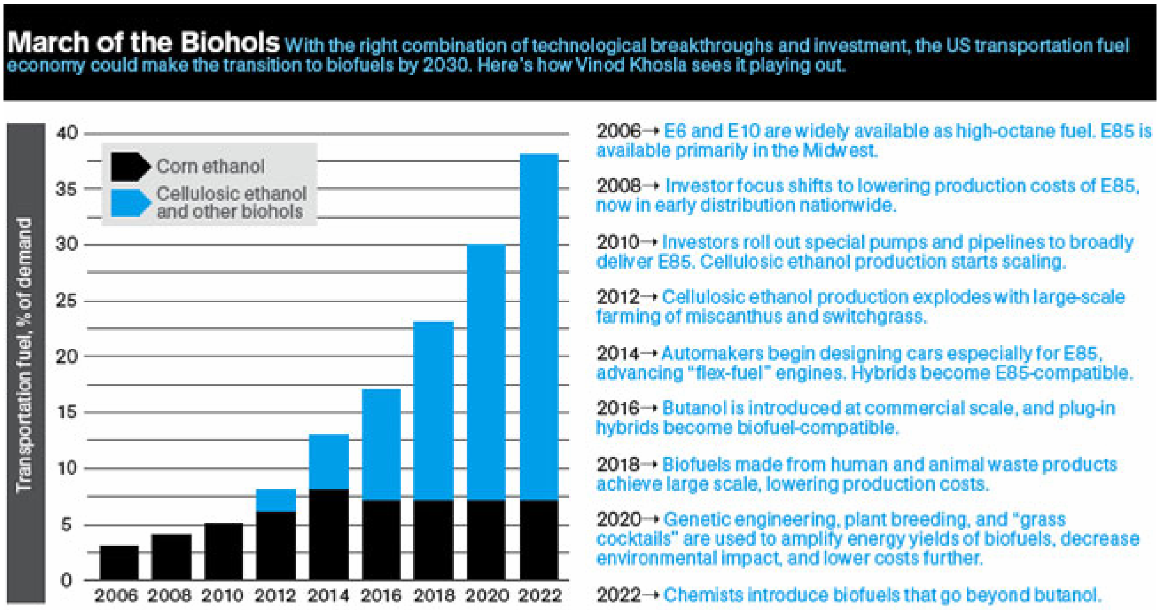
While the chart above details the common pathways, the chart below highlights a selection of companies working on each individual path. It is notable that companies vary from small, privately funded startups to behemoths such as BP, Dupont. In addition to the biofuels companies themselves, many entrepreneurs are working on improving the feedstocks themselves. This is the power of the innovation ecosystem. Khosla Ventures' investments are bolded - a short description of each company can be found in Appendix B.



Trajectory / Predictable Unpredictability – "What Is" vs. "What Can Be":

To succeed, we need technologies that have certain characteristics – rapid evolution, short innovation cycles, and an ability for the technology to scale. In practice, this criteria is a measure of a given venture/technology to get up and running quickly – the ability to get the first plant operational (for example, Range Fuels is beginning construction of its 100-million gallon cellulosic ethanol plant in 2007 – just 2 years after its founding). Innovators don't have large balance sheets – they can't build plants if the "cost of proof" is too high. Moreover, a quicker innovation cycle gives a venture the ability to try multiple options, continuous improvements, and seek the advantages that initial occupancy of a market bring and results (whether good or bad) are available relatively quickly. Contrast this with an oil refinery – in the US, no refinery has been built in 30 years due to the high costs, environmental problems, and regulation associated with it. Lynn Westfall, the chief economist of Tesoro (an oil refinery owner) notes that ‘"If you were to ask us to go build a brand new refinery anywhere in the world, I would tell you you'd be lucky to have it up and running in six or seven years," Westfall says. "And then you'd need 10 to 15 years of today's margins to pay it back. So building a new refinery is a 20-year bet that margins are going to remain very high."’[2] In addition, refineries tend to be very energy intensive - Petroleum refining is the most energy-intensive manufacturing industry in the United States. In 2002, the U.S. refining industry consumed 6.391 quads (quadrillion Btu, or 10e15 Btu) of energy, accounting for about 28% energy consumption in U.S. manufacturing.[3] In the same period as it takes to get one refinery up-and-running, cellulosic ethanol technologies could go through multiple innovation cycles – evolving rapidly to meet the needs of the marketplace.

The first, and perhaps most important factor when we consider climate change technology, is its scalability. Simply put – can it be produced, stored, and distributed on a wide enough scale to be material in carbon emission reductions? With biofuels, a significant factor in estimating its future viability is the availability of its feedstocks (how much land will it use? Will it continue to improve its yields?) and its consistent, reliable availability as the biofuel scales to commercial production levels. Classic biodiesel, to take one example, is so land inefficient as to render it un-scalable even if it achieved competitive cost targets (which it is unlikely to do). Will the trajectory of a some technologies lead to dead ends (e.g. vegetable biodiesel) or better and better supply chain, yields, costs, etc (cellulosic ethanol)? We expect a declining cost with scale for cellulosic ethanol. As the biomass ecosystem develops, with new crop rotation practices, better genetics for energy crops and a variety of related reasons -like scale, better logistics, farming equipment, better transportation, handling etc- all result in declining costs as the technology develops and matures. The net result is that the ecosystem development drops costs for everyone, and keeps the technology on a positive trajectory with improving competitiveness. In the graph below, we highlight one potential pathway of how biofuels might make a material impact in our transportation needs – using corn ethanol to prime the infrastructure for cellulosic ethanol and other biofuels (note that the graph is primary for illustrative purposes and we expect surprises in its evolution).


March of the Biohols With the right combination of technological breakthroughs and investment, the US transportation fuel economy could make the transition to biofuels by 2030. Here's how Vinod Khosla sees it playing out.

2006 → E6 and E10 are widely available as high-octane fuel. E85 is available primarily in the Midwest.

2008 → Investor focus shifts to lowering production costs of E85, now in early distribution nationwide.

2010 → Investors roll out special pumps and pipelines to broadly deliver E85. Cellulosic ethanol production starts scaling.

2012 → Cellulosic ethanol production explodes with large-scale farming of miscanthus and switchgrass.

2014 → Automakers begin designing cars especially for E85, advancing "flex-fuel" engines. Hybrids become E85-compatible.

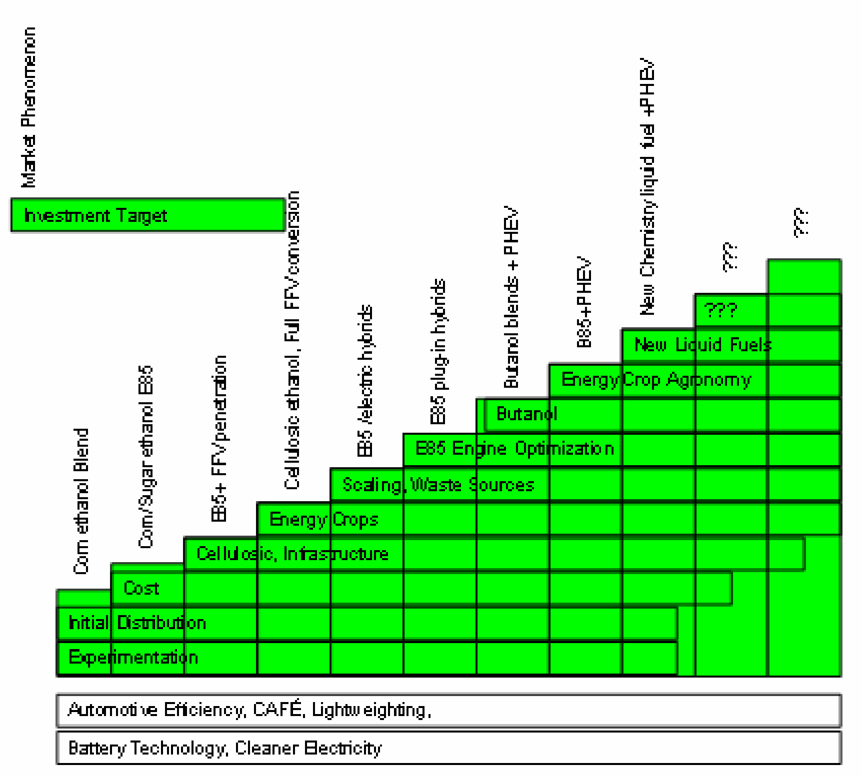
2016 → Butanol is introduced at commercial scale, and plug-in hybrids become biofuel-compatible.

2018 → Biofuels made from human and animal waste products achieve large scale, lowering production costs.

2020 → Genetic engineering, plant breeding, and "grass cocktails" are used to amplify energy yields of biofuels, decrease environmental impact, and lower costs further.

2022 → Chemists introduce biofuels that go beyond butanol.

Each development in biofuels empowers innovators to experiment with the next set of innovations, leaded to surprising pathways. One such potential pathway is illustrated below.



The Evolutionary Stair-step

How does the innovation ecosystem play out? The graph above illustrates one potential pathway for a new technology to step up from stage to stage to an eventual petroleum replacement scenario. A dominant entity like oil cannot be felled in one swoop; rather, we need a series of steps, each building upon the previous and each justifiable on its own economic merits (and thus able to attract private capital). With biofuels, corn ethanol provides the initial starting point; it is vital in priming the infrastructure for the production, storage, and distribution of biofuels on a large stage (we expect corn ethanol production to level of at 15 billion gallons or so) – roughly equating to the first three blocks of the path above. Building upon this, the ramp-up in production of cellulosic fuels (at below $1.25 per gallon production cost or $2.00 per gallon sale price) combined with the increasing penetration of FFV vehicles will lead to an explosion in cellulosic ethanol usage – utilizing the infrastructure put in place by corn ethanol (in fact, we see the possibility of some cellulosic plants as add-ons to corn ethanol plants, increasing their economic viability). In the long run, the innovation ecosystem will further build on this platform (perhaps through one of the technical approaches we outlined previously). In the long run, combining these factors with likely increases in CAFE (Corporate Average Fuel Economy), energy efficiency, and continual increase in feedstock yields (from cellulose to waste) will result in the development of new, unconventional ideas that are unfathomable - at least today. This step-by-step system, fueled by technological developments, market asset allocation, and public action working in conjunction has and will continue to yield significant results and make today's unthinkable scenarios tomorrows conventional wisdom.

Much of our frustration is with critics who argue from the "what is" as opposed to "what can be" approach. We often see the circular argument that "if it isn't true today, it won't be true tomorrow and hence is not worth working on". Our approach is one that says every major problem is a major opportunity and often (but not always) it is just a question of focusing attention and resources on a difficult technical problem and it will be solved. We are technology optimists. No problem, no solution, no opportunity. A big problem to us means a big opportunity. Most of the problems in energy technology seem eminently solvable and suffer primarily from a lack of focus from the best minds in the country on it. This "what is" versus "what can be" approach is most visible in cellulosic biofuels. The technology is eminently doable, likely to be cheaper than not only corn ethanol but more importantly gasoline at most recent prices of oil. From our perspective, the generic approach to any big problem (challenge) is as follows: add the best minds to the problem, so that your problem is being tackled by the smartest people in the world – and not just the smartest people in that industry with fixed narrow mindsets on what is possible. The internet lured the brightest minds (from all fields) in the 90's, and green energy can do the same in the coming decade. Having attracted the people, we must pick the best ideas around, and allow them time to ferment with the zeal of entrepreneurial energy. Finally, appeal at some level to greed – the potential for this market is larger than any other one that we have encountered and entrepreneurs, venture capitalists, technologists and scientists will pursue it**.** Google ten years ago was a vision – today, its worth over a $100 billion. One of the many green-energy startups could be next. **The power of ideas fueled**

by entrepreneurial energy is the key to displacing oil. This is the innovation ecosystem at work and it thrives on big problems and big opportunities.

For those of you who don't believe this is possible, there are many precedents for massive change. In 1982 when Sun Microsystems was started, it was said that one could not compete against IBM, Digital Equipment Corporation, Data General, Burroughs, Control Data and other stalwarts of the computer business. Most of them are now gone and a few have adjusted, humbled by the seemingly “toyish” microprocessor. In 1996, I got in a room with the CEO’s of nine major US media companies, including the Washington Post, New York Times, Knight-Ridder, Tribune, Cox, Times-Mirror and others and tried to explain how the internet would disrupt their business models, and little companies like Yahoo, Ebay, Google and others would be a threat. Today Google is worth as much as all of them combined. The pharmaceutical companies went through a similar experience, ignoring biotechnology in the early days. Ten years ago every major telecommunications company noted that they would never adopt the internet IP protocol as their core network just as we were starting a telecommunications equipment company called Juniper to produce IP equipment. Their industry had a hundred years of legacy infrastructure, hundreds of billions in investment, and hundreds of thousands of union employees (sound familiar in the energy sector?). Major “experts” like AT&T laughed at the idea that all long distance calls would be virtually free to consumers. When at the peak of their market cap I predicted that companies like AT&T, Lucent, and Nortel could go bankrupt, many people laughed. Today, for failing to heed that trend, major players like AT&T are mere brands, their company sold for a song. Less than ten years later, yesterday’s “unthinkable fact” is today’s “conventional wisdom”. Just because we can’t always predict or explain the path of technology breakthroughs does not mean that they will not happen. In many ways, the five pound brick “mobile” phone of 1985 fulfilled a similar role to what corn ethanol is doing today - much as we may not have predicted exactly what the phone of 2007 would be like back in 1985, the degree of change was easily apparent. With the best people (from the scientists and venture capitalists to the entrepreneurs) and the best opportunities will come the best results.

The Role of Policy – and dealing with misguided environmentalism

The problem of idealism vs. pragmentalism vs politicism is a vital issue; we have to be careful to adopt the best solutions, and not simply the most political expedient solution. At the policy level, our focus should be on large, material solutions instead of idealistic pie-in-the-sky scenarios. We believe a cellulosic renewable fuels standard of some level is needed (and likely), along with the likely passage of higher CAFE standards and the eventual adoption of a carbon taxation scheme. Additionally, the removal of oil subsidies (both direct and indirect) is paramount – the most profitable industry on the planet does not need to continue feeding at the public trough.

The role of policy is vital in combating another problem – idealistic, unscaleable solutions vs. realistic and pragmatic alternatives. There are undoubtedly risks associated with biofuels (the biomass yields being perhaps the most important example), and we’ve noted some of them here. In particular, the risks of “greenwashing” are immense – the adoption of feel-good actions instead of genuine solutions to the problem at hand. The Indonesian/Malaysian biodiesel (where the clearing of rainforest land for production led to increased emissions, as compared to regular petrodiesel – while being subsidized by the EU), is an example of misplaced idealism. In San Francisco, the usage of grease from restaurants to generate biodiesel (to run the buses) is another (less egregious) example – the resulting fuel cannot meet quality and consistency standards, and cannot scale to be a large scale solution. Many dreamers have a tendency to paint idealistic scenarios – especially when they have the ability to promise them with government funding.

A standard question about biofuels is as to the role of subsidies – what is appropriate, for how long, and so forth. We believe that direct government aid for biofuels can be appropriate for a limited time depending on the circumstances - developmental aid is sometimes necessary to get the right trajectory started. Subsidies should be used only to help technologies and approaches that are "getting started". Primarily, we think limited government subsidies (loan guarantees for initial commercial plants, for example) can be a substantial boon in mitigating the technological and development risks associated with new approaches, while requiring limited amounts of actual capital from public coffers. Government should not be in the business of picking winners – rather, its role ought to be in setting standards and criteria (i.e., - any approach that can reduce carbon emissions per mile driven by 50%, as compared to gasoline), and allowing any nascent technology that meets those hurdles to be eligible for limited commercialization aid, and helping it transition downward on its cost curve. Elsewhere, government mandates can help define a market and have a multiplicative effect on private capital– for example, the recently approved Renewable Fuel Standard (36 billion gallons by 2020) acts as an implicit guarantee that a market will exist for these fuels. In practice, we're confident that cellulosic ethanol production (fueled by private capital) in 2020 will far exceed that threshold at prices below that of gasoline.

When should subsidies be limited? We believe in the pragmatic approach – if a technology cannot achieve unsubsidized market-competitiveness in 7-10 years, it is probably not a viable candidate for government help, and is more likely to divert public resources from genuine, climate-change solutions. Beyond the developmental period, the aid becomes just another subsidy with little multiplicative benefit (to society) over the longer term – a poor investment of limited public resources. Moreover, public resources cannot (and should not) keep an approach viable forever - in the long run (as pragmentalists), we are convinced that nothing can be scaled without the backing of private capital.

The Cost of the Status-Quo

While the focus of this paper is on the various pathways that are available for the development of biofuels, it's worth discussing why the pathway ought to be explored in the first place. The world today is facing a climate change crisis of epic proportions, and our continued dependence on petroleum is a significant cause of it. Beyond climate change, petroleum carries geopolitical risk (an increase Middle Eastern dependence, as well as the dependence on unsavory regimes such as Sudan and Venezuela's), high military costs and economy wide risks and commodity risk of a resource that is being depleted – rapidly.

Our primary problem with many critics of biofuels is their unwillingness (or ignorance) of the costs we face today – fundamentally, we do not believe that the current status quo is a sustainable, long-term solution. The Stern report estimated that climate change could result in a 20% reduction in worldwide GDP[4]; and (it and other reports) note that the impact will be disproportionately felt by poor countries. Holland can deal with the cost of rising sea levels – can Bangladesh do the same? Clearly, the switch away from a petroleum-driven economy will involve its own set of expenditures and risks. The key question is which set of risks, of biofuels or of oil, should we be taking? It is unlikely that we will find an ideal replacement for oil with no risks or downsides.

Critics also fail to understand the role of the innovation ecosystem how it may mitigate many of these risks – the combination of smart people, capital, and government will allow us to do far more than many perceive. As a society, we face the problem of risk management – what set of risks do we intend to take? **In the end, we come down on the side of actively tackling the risks inherent in the status quo of oil. We prefer the risks of biofuels over the risks of oil because we, in our view, have much stronger weapons to advance the biofuels ecosystem.**

Summary

The world has changed but the pundits don't know it. The power of ideas fueled by entrepreneurial energy has created a whole new world of possibilities, and the "innovation ecosystem" is in full bloom. The utilization of biomass (and potentially waste) as a feedstock offers significant benefits not present with current methods of fuel production; furthermore, the lack of optimization in these feedstocks and other technologies offers room for yields of fuel to increase dramatically. In conjunction with the increased research into agronomy practices the widespread adoption of biofuels will not result in any substantial "crowding out" of traditional agriculture, but can significantly mitigate our climate change risks.

Cellulosic ethanol is ready and cost-effective using today's technologies and commercial plants are being built right now. In this white paper, we've highlighted a selection of approaches towards achieving the goal of environmentally-friendly transportation fuels and an eventual replacement for petroleum. We have our favorites – ideas we believe in and ideas we don't. Nott all oil wells have the same production costs – the Saudi wells can produce oil at near-zero marginal costs[5], while Canadian tar sand production has marginal extraction costs of over $30 per barrel (not including any initial startup costs).[6] From the standpoint of biofuels, we believe that that all technologies that can produce a gallon equivalent of ethanol at a $1.25 (or below) will be competitive and have a substantial market. Many technologies will be successful and a number of potential markets exist – gasoline, diesel, aviation fuel, heating oil, and even plastics! The criteria for investment across the various markets is clearly different, but any technology that reaches the $1.25 per gallon (of ethanol equivalent) price point will be successful.

In time, there will certainly be a culling of ideas towards those that prove themselves in more rigorous tests and those that fall aside due to unsatisfactory economics, an inability to scale, a failed process, simply victim to a better fuel chemistry, or maybe even just bad luck. It is certain that there will be setbacks in the process – but it is also certain that their will be successes, accidental discoveries, and developments out of left field.

Appendix A: Potential Scenarios for Land Use

Scenarios - Summary

Scenario	Waste Resources (% of total ethanol demand in 2030)	Winter Cover Crop - % of annual crop land/ acres	Winter Cover Crop Yield (Tons Per Acre)	Excess Forest Biomass (Millions of Dry Tons)	Biofuel Yields (Gallons per Ton)	Dedicated Land Use @ 24/18/12 tons/acre (Millions of Acres)	Net Land Use @ 24/18/12 tons/ acre (Millions of Acres)
1:	10%– 15B gallons	50% – 159M	3-4.6	70% -158Mt	90-110	13.6 / 18.2 / 27.3	-1.9 / 2.7 / 11.8
2:	-	50% – 159M	3-4.6	50% -113Mt	90-110	21.0 / 28.1 / 42.1	5.5 /12.6 /26.6
3:	-	50% – 159M	3-4.6	50% -113Mt	90-130	12.5/16.6/25.0	-3.0 / 1.1 / 9.5
4:	-	50% – 159M	3-4.6	70% -158Mt	90-130	10.6/14.2/21.3	-4.9 / 1.3 / 5.8
5:	-	50% – 159M	3-4.6	100% -226Mt	90-130	7.9/10.5/15.7	-7.6 / -5.0 / 0.2
6:	10% –15B gallons	70% – 221M	3-4.6	100% -226Mt	90-130	0	-15.5

General Notes:

1. We estimate that 150B gallons of cellulosic ethanol are needed in 2030 to replace most light-vehicle gasoline usage. How do we get there? The EIA energy outlook (published BEFORE the recent energy bill passage) projects light-vehicle usage of 11.15M [7] barrels/day of oil equivalent in 2030 – or about 171B gallons annually. We assume a 20% discount on this demand to reflect updated CAFE standards, and an ethanol mileage discount of 15% - giving us equivalent ethanol demand of 160B gallons (if every car was a Flex Fuel Vehicle). We assume that by 2030, 90% of the fleet consists of FFV's, leading to ethanol demand of 144B gallons (we have thus used 150B gallons to be conservative). In some scenarios, we exceed this projection without dedicated crop land, and production numbers reflect that.
2. Biomass from waste production is modeled in some scenarios. Waste refers to organic waste, municipal waste, industrial waste, flue gases from steel mills, and other biomass waste.
3. Current CAFE laws are assumed to reduce gasoline demand. Additional ICE engine efficiency/higher CAFE could substitute for higher efficiency on ethanol assumed by 2030. Any of the efficiency breakthroughs mentioned here but not assumed the calculations could dramatically improve all the scenarios.
4. Yield projections (tons per acre) are based on fertile, rainfed (40 inch rain region) land. The usage of degraded land will result in lower yields. Crop variety and yield variations are averaged for modeling purposes.
5. We assume that the primary source of dedicated land for energy crops will be cropland, but commercial reduction in today's forest resource usage (i.e. - more paper mill closures) could be offset by using it for biofuels - while also reducing the amount of cropland needed.

6. We believe that replacing diesel may require an additional 20M acres in cropland, but it is not modeled here. Many of the gasoline use scenarios result in excess biomass that could be used for diesel production and other purposes.
7. No recovery of degraded land is assumed because of good perennial growth; long cycle crop rotation practices are assumed, but no increase in yields from such practices is modeled.
8. In 2008, the USDA projects corn ethanol production of 9.3B gallons. At 150 bushels per acre and 2.8 gallons per bushel, this equates to 22.1M acres of expected corn production for biofuels. We assume only 70% of this land is recovered because 30% of corn ethanol byproduct is used as feed, and that demand still needs to be met.
9. Gasoline takes approx 2-2.5 gallons of water to produce 1 gallon (as per NREL[8]) - production of 1 gallon of cellulosic ethanol (using Range/Coskata like thermochemical processes) would use 1 gallon of water. Assuming an ethanol mileage discount of 15% in 2030, net water usage per mile driven with cellulosic ethanol is approximately 47-58% that of gasoline refining.
10. Our yield assumptions assume adoption of thermochemical processes (such as those of Range and Coskata), as opposed to standard bio-fermentation. The maximum theoretical yield (for switchgrass) is 111 gal/ ton for biochemical processes, and 198.4 gal/ton for thermochemical processes ("Cellulosic Biofuel Technologies", Professor David Bransby). Though historical chemical processes often reach 75-80% of theoretical maximum yield, the most optimistic scenario here (130 gallons/ton) for biofuel yield is modeled at 65% net efficiency.

Scenarios

Scenario 1

	KV Cellulosic Ethanol Production Estimates	Waste Ethanol Production Estimates	Ethanol Yield (Gals/Ton)	Total Biomass Needed	Winter Cover Crop Acres	Winter Cover Crop Yield	Forest Excess Biomass	Forest Biomass Yield	Biomass needed from dedicated cropland	Expected Yield (Tons/ac)	Acres needed at projected yield	Acres needed at 75% of projected yield	Acres needed at 50% of projected yield
	(Gallons - Billions)	(Gallons - Billions)	(best tech)	(Tons - Millions)	(Acres - Millions)	(tons/ac)	(Tons - Millions)	(tons/ac)	(Tons - millions)	(Tons - millions)	(Tons - millions)	(Tons - millions)	(Tons - millions)
2015	5.0	0.0	102.3	48.9	4.1	3.4	20.8	10.9	14.0	10.9	1.3	1.7	2.6
2020	30.0	3.0	107.5	251.1	42.9	3.8	68.3	15.4	19.4	15.4	1.3	1.7	2.5
2025	87.6	8.0	110.0	724.1	142.5	4.2	125.5	20.5	0.0	20.5	0.0	0.0	0.0
2030	150.0	15.0	110.0	1227.3	158.5	4.6	158.0	24.5	334.2	24.5	13.6	18.2	27.3

How Do We Get There?

Total Biomass	=	Winter Cover Crops:	Forest Excess Waste:	Dedicated Crop Land:
2015: 49M tons	=	14M tons	21M tons	14M tons
2020: 251M tons	=	163M tons	68M tons	19M tons
2025: 724M tons	=	599M tons	126M tons	0M tons
2030: 1227M tons	=	735M tons	158M tons	334M tons

2030 - How Much Land Do We Need?

	24 t/ac	18 t/ac	12 t/ac
Displaced Land - Due to Dedicated Energy Crops	13.6	18.2	27.3
Reclaimed Land - based on 2008 corn ethanol production, assuming 70% land recovery	-15.5	-15.5	-15.5
Net Land Use (Excluding Winter Cover Crops, Forest Excess Waste)	**-1.9M acres**	**2.7M acres**	**11.8M acres**

Scenario 2

	KV Cellulosic Ethanol Production Estimates	Waste Ethanol Production Estimates	Ethanol Yield (Gals/Ton)	Total Biomass Needed	Winter Cover Crop Acres	Winter Cover Crop Yield	Forest Excess Biomass	Forest Biomass Yield	Biomass needed from dedicated cropland	Expected Yield (Tons/ac)	Acres needed at projected yield	Acres needed at 75% of projected yield	Acres needed at 50% of projected yield
	(Gallons - Billions)	(Gallons - Billions)	(best tech)	(Tons - Millions)	(Acres - Millions)	(tons/ac)	(Tons - Millions)	(tons/ac)	(Tons - millions)	(Tons - millions)	(Tons - millions)	(Tons - millions)	(Tons - millions)
2015	5.0	0.0	102.3	48.9	4.1	3.4	19.2	10.9	15.6	10.9	1.4	1.9	2.8
2020	30.0	0.0	107.5	279.0	42.9	3.8	47.7	15.4	67.9	15.4	4.4	5.9	8.8
2025	80.0	0.0	110.0	727.3	142.5	4.2	76.1	20.5	52.6	20.5	2.6	3.4	5.1
2030	150.0	0.0	110.0	1363.6	158.5	4.6	113.0	24.5	515.5	24.5	21.0	28.1	42.1

How Do We Get There?

Total Biomass	=	Winter Cover Crops	Forest Excess Waste	Dedicated Cropland
2015: 49M tons	=	14M tons	19M tons	16M tons
2020: 279M tons	=	163M tons	48M tons	68M tons
2025: 727M tons	=	599M tons	76M tons	53M tons
2030: 1364M tons	=	735M tons	113M tons	516M tons

2030 - How Much Land Do We Need?

	24 t/ac	18 t/ac	12 t/ac
Displaced Land - Due to Dedicated Energy Crops	21.0	28.1	42.1
Reclaimed Land - based on 2008 corn ethanol production, assuming 70% land recovery	-15.5	-15.5	-15.5
Net Land Use (Excluding Winter Cover Crops, Forest Excess Waste)	**5.5M acres**	**12.6M acres**	**26.6M acres**

Scenario 3

	KV Cellulosic Ethanol Production Estimates	Waste Ethanol Production Estimates	Ethanol Yield (Gals/Ton)	Total Biomass Needed	Winter Cover Crop Acres	Winter Cover Crop Yield	Forest Excess Biomass	Forest Biomass Yield	Biomass needed from dedicated cropland	Expected Yield (Tons/ac)	Acres needed at projected yield	Acres needed at 75% of projected yield	Acres needed at 50% of projected yield
	(Gallons - Billions)	(Gallons - Billions)	(best tech)	(Tons - Millions)	(Acres - Millions)	(tons/ac)	(Tons - Millions)	(tons/ac)	(Tons - millions)	(Tons - millions)	(Tons - millions)	(Tons - millions)	(Tons - millions)
2015	5.0	0.0	104.9	47.7	4.1	3.4	19.2	10.9	14.4	10.9	1.3	1.8	2.6
2020	30.0	0.0	113.0	265.6	42.9	3.8	47.7	15.4	54.5	15.4	3.5	4.7	7.1
2025	82.1	0.0	121.7	674.7	142.5	4.2	76.1	20.5	0.0	20.5	0.0	0.0	0.0
2030	150.0	0.0	130.0	1153.8	158.5	4.6	113.0	24.5	305.7	24.5	12.5	16.6	25.0

How Do We Get There?

Total Biomass		Winter Cover Crops	Forest Excess Waste	Dedicated Crop Land
2015: 48M tons	=	14M tons	19M tons	14M tons
2020: 266M tons	=	163M tons	48M tons	55M tons
2025: 675M tons	=	599M tons	76M tons	0M tons
2030: 1154M tons	=	735M tons	113M tons	305M tons

2030 - How Much Land Do We Need?

	24 t/ac	18 t/ac	12 t/ac
Displaced Land - Due to Dedicated Energy Crops	12.5	16.6	25.0
Reclaimed Land - based on 2008 corn ethanol production, assuming 70% land recovery	-15.5	-15.5	-15.5
Net Land Use (Excluding Winter Cover Crops, Forest Excess Waste)	**-3M acres**	**1.1M acres**	**9.5M acres**

Scenario 4

	KV Cellulosic Ethanol Production Estimates	Waste Ethanol Production Estimates	Ethanol Yield (Gals/Ton)	Total Biomass Needed	Winter Cover Crop Acres	Winter Cover Crop Yield	Forest Excess Biomass	Forest Biomass Yield	Biomass needed from dedicated cropland	Expected Yield (Tons/ac)	Acres needed at projected yield	Acres needed at 75% of projected yield	Acres needed at 50% of projected yield
	(Gallons - Billions)	(Gallons - Billions)	(best tech)	(Tons - Millions)	(Acres - Millions)	(tons/ac)	(Tons - Millions)	(tons/ac)	(Tons - millions)	(Tons - millions)	(Tons - millions)	(Tons - millions)	(Tons - millions)
2015	5.0	0.0	104.9	47.7	4.1	3.4	20.8	10.9	12.8	10.9	1.2	1.6	2.3
2020	30.0	0.0	113.0	265.6	42.9	3.8	68.3	15.4	33.9	15.4	2.2	2.9	4.4
2025	88.1	0.0	121.7	724.1	142.5	4.2	125.5	20.5	0.0	20.5	0.0	0.0	0.0
2030	150.0	0.0	130.0	1153.8	158.5	4.6	158.0	24.5	260.7	24.5	10.6	14.2	21.3

How Do We Get There?

Total Biomass		Winter Cover Crops	Forest Excess Waste	Dedicated Crop Land
2015: 48M tons	=	14M tons	21M tons	13M tons
2020: 266M tons	=	163M tons	68M tons	34M tons
2025: 724M tons	=	599M tons	126M tons	0M tons
2030: 1154M tons	=	735M tons	158M tons	261M tons

2030 - How Much Land Do We Need?

	24 t/ac	18 t/ac	12 t/ac
Displaced Land - Due to Dedicated Energy Crops	10.6	14.2	21.3
Reclaimed Land - based on 2008 corn ethanol production, assuming 70% land recovery	-15.5	-15.5	-15.5
Net Land Use (Excluding Winter Cover Crops, Forest Excess Waste)	**-4.9M acres**	**-1.3M acres**	**5.8M acres**

Scenario 5

	KV Cellulosic Ethanol Production Estimates	Waste Ethanol Production Estimates	Ethanol Yield (Gals/Ton)	Total Biomass Needed	Winter Cover Crop Acres	Winter Cover Crop Yield	Forest Excess Biomass	Forest Biomass Yield	Biomass needed from dedicated cropland	Expected Yield (Tons/ac)	Acres needed at projected yield	Acres needed at 75% of projected yield	Acres needed at 50% of projected yield
	(Gallons - Billions)	(Gallons - Billions)	(best tech)	(Tons - Millions)	(Acres - Millions)	(tons/ac)	(Tons - Millions)	(tons/ac)	(Tons - millions)	(Tons - millions)	(Tons - millions)	(Tons - millions)	(Tons - millions)
2015	5.0	0.0	104.9	47.7	4.1	3.4	22.4	10.9	11.2	10.9	1.0	1.4	2.0
2020	30.0	0.0	113.0	265.6	42.9	3.8	88.4	15.4	13.8	15.4	0.9	1.2	1.8
2025	90.2	0.0	121.7	740.9	142.5	4.2	142.3	20.5	0.0	20.5	0.0	0.0	0.0
2030	150.0	0.0	130.0	1153.8	158.5	4.6	226.0	24.5	192.7	24.5	7.9	10.5	15.7

How Do We Get There?

Total Biomass	=	Winter Cover Crops	Forest Excess Waste	Dedicated Crop Land
2015: 48M tons	=	14M tons	22M tons	11M tons
2020: 266M tons	=	163M tons	88M tons	14M tons
2025: 741M tons	=	599M tons	142M tons	0M tons
2030: 1154M tons	=	735M tons	226M tons	193M tons

2030 - How Much Land Do We Need?

	24 t/ac	18 t/ac	12 t/ac
Displaced Land - Due to Dedicated Energy Crops	7.9	10.5	15.7
Reclaimed Land - based on 2008 corn ethanol production, assuming 70% land recovery	-15.5	-15.5	-15.5
Net Land Use (Excluding Winter Cover Crops, Forest Excess Waste)	**-7.6M acres**	**-5M acres**	**0.2M acres**

Scenario 6

	KV Cellulosic Ethanol Production Estimates	Waste Ethanol Production Estimates	Ethanol Yield (Gals/Ton)	Total Biomass Needed	Winter Cover Crop Acres	Winter Cover Crop Yield	Forest Excess Biomass	Forest Biomass Yield	Biomass needed from dedicated cropland	Expected Yield (Tons/ac)	Acres needed at projected yield	Acres needed at 75% of projected yield	Acres needed at 50% of projected yield
	(Gallons - Billions)	(Gallons - Billions)	(best tech)	(Tons - Millions)	(Acres - Millions)	(tons/ac)	(Tons - Millions)	(tons/ac)	(Tons - millions)	(Tons - millions)	(Tons - millions)	(Tons - millions)	(Tons - millions)
2015	5.0	0.0	104.9	47.7	4.1	3.4	22.4	10.9	11.2	10.9	1.0	1.4	2.0
2020	31.4	3.0	113.0	251.8	42.9	3.8	88.4	15.4	0.0	15.4	0.0	0.0	0.0
2025	102.0	8.0	121.7	772.4	150.0	4.2	142.3	20.5	0.0	20.5	0.0	0.0	0.0
2030	177.6	15.0	130.0	1251.0	221.0	4.6	226.0	24.5	0.0	24.5	0.0	0.0	0.0

How Do We Get There?

Total Biomass	=	Winter Cover Crops	Forest Excess Waste	Dedicated Crop Land
2015: 49M tons	=	14M tons	22M tons	11M tons
2020: 251M tons	=	163M tons	88M tons	0M tons
2025: 772M tons	=	630M tons	142M tons	0M tons
2030: 1251M tons	=	1025M tons	226M tons	0M tons

2030 - How Much Land Do We Need?

	24 t/ac	18 t/ac	12 t/ac
Displaced Land - Due to Dedicated Energy Crops	0.0	0.0	0.0
Reclaimed Land - based on 2008 corn ethanol production, assuming 70% land recovery	-15.5	-15.5	-15.5
Net Land Use (Excluding Winter Cover Crops, Forest Excess Waste)	**-15.5M acres**	**-15.5M acres**	**-15.5M acres**

Appendix B: KV Biofuels Portfolio Companies

Corn/Sugar Fuels:

Cilion: Cilion is building destination ethanol plants, promising to be the cheapest and greenest ethanol from initially corn and incorporating cellulosic technologies as they come online.

Hawaii Bio: Hawai‘i Bioenergy’s mission is to determine the feasibility and viability of locating and operating integrated ethanol bio-refinery plants in the Hawaiian Islands.

Ethos: Ethos is developing sugarcane and cellulosic biofuels in Latin America (excluding Brazil.

Cellulosic Fuels:

Range Fuels: Range is building the first commercial cellulosic ethanol plant in the US using a proprietary anaerobic conversion and heterogeneous catalyst technology.

Mascoma: Mascoma Corporation is developing proprietary bioprocess technologies for cost-effective conversion of cellulosic biomass to ethanol, drastically reducing the need for external enzymes.

Coskata: Coskata is commercializing a fermentation technology for the production of fuel-grade ethanol from syngas.

Lanzatech: LanzaTech is developing a proprietary fermentation technology to convert industrial flue gas from steel mills as a resource for biofuels production.

Future Fuels:

LS 9: LS9, Inc., the Renewable Petroleum CompanyTM, is combining synthetic biology and cellulosic feedstocks to make petroleum replacements from bacteria using fermentation.

Gevo: Gevo is developing technologies for the bacterial production of biobutanol from sugars and cellulose.

Amyris: Amyris Biotechnologies is translating the promise of synthetic biology into industrial production of fermentation diesel and higher alcohols from sugars and cellulose.

Kior: Kior is using its patented Biomass Catalytic Cracking (BCC) process to convert biomass into a biocrude useable as crude oil.

Engines:

Transonic: Transonic is using proprietary fuel injection technology to increase the efficiency of gasoline engines.

Ecomotors: Ecomotors has a uniquely designed diesel engine that can generate significantly more power while utilizing less space.

Tula Technologies: Tula Technologies is applying digital technology to sharply improve the fuel efficiency of engines in both the existing and future fleet.

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[1] NSF. 2008. *Breaking the Chemical and Engineering Barriers to Lignocellulosic Biofuels: Next Generation Hydrocarbon Biorefineries.* Ed. George W. Huber, University of Massachusetts Amherst. National Science Foundation. Chemical, Bioengineering, Environmental, and Transport Systems Division. Washington D.C.

[2] http://www.npr.org/templates/story/story.php?storyId=10554471

[3] Petrochemical Refining: Technology and Economics, 5th Edition, James H. Gary, Glenn E. Handwerk, Mark J. Kaiser, CRC Press, 2007.

[4] http://www.hm-treasury.gov.uk/independent_reviews/stern_review_economics_climate_change/stern_review_report.cfm

[5] http://pangea.stanford.edu/~jshragge/OilWar/OPEC.html

[6] http://www.house.gov/jec/publications/109/06-26-06_oil_sands.pdf

[7] http://www.eia.doe.gov/oiaf/aeo/pdf/appa.pdf

[8] http://www.swhydro.arizona.edu/archive/V6_N5/feature4.pdf