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What matters in Biofuels & where are we?

Given the likely continued dominance of the internal combustion engine, cellulosic and sugar-derived fuels offer one of the lowest risk advances to quickly and affordably achieve low-carbon transportation. Furthermore, substituting higher value bio-chemicals for petro-chemicals, will promote enhanced sustainability across a wealth of industries and offer a critical step along the path to weaning the world off of oil. There also are measurable economic and national security benefits to drastically reducing the reliance on global oil.

Amyris was a signature IPO in this space. In addition to Amyris, several biofuels companies are actually starting their businesses with high value chemicals, a lower-risk pathway to profitably move down the cost and efficiency learning curve to fuels. The value of chemicals produced by biological processes can be up to 2 to 10 times higher than biofuels, while commanding billion dollar markets. I believe the medium term (5 year) "safe from oil price volatility" price target for biofuels is to be under $60 to $70 barrel of oil equivalent, unsubsidized for global competitiveness. In the US, subsidies and the RFSII mandate make significantly higher prices viable. Of course, if oil prices soar as many expect, (e.g. to $150 to $200 per barrel by 2015 to 2020), or even stay at current levels ($90 per barrel), higher cost biofuels will be viable. About 12 billion gallons of corn-based biofuel (i.e. ethanol) per year are already being produced in the United States and selling for $1.50 to $2.50 per gallon (with a roughly equivalent amount of sugar-cane based ethanol in Brazil, selling for $1.00 to $2.25 per gallon)[1], representing a $30 billion and growing market for new fuels to play in. In fact the mandated renewable fuels market in the US alone is $90 billion at these prices by 2022. I predict that long before 2022, half a dozen technologies within and outside our portfolio will be market competitive and will blow away the cost structure of corn ethanol.

However, I consider corn (and sugarcane in the longer run) ethanol to be transitional technologies. To achieve the US renewable fuels target of 36 billion gallons in 2022 and beyond, biofuels will need to be produced largely from high yield non-food biomass sources. I also envision advanced biofuels moving well beyond ethanol and diesel to hydrocarbon fuels: renewable crude oil, drop-in diesel, gasoline, jet fuel and other petrochemicals. Through a combination of diverse feedstock and diverse end products, bio-derived hydrocarbons and alcohols have the potential to replace an entire industry.

The old fashioned bias among traditionalists, mostly Luddites unfamiliar with the vibrant new research especially in startups, is that Fischer-Tropsch synthesis (FT) of liquid hydrocarbons from gasified coal and biomass is the only path to producing enough fuel to replace conventional crude oil. Frankly, this is nonsense. Many also assert that biofuels cannot scale to the quantity needed without impacting food availability, but the data suggest otherwise and I briefly discuss this below.

Common production technologies for fuels or fuels precursors are sugar fermentation, synthesis gas (syngas) fermentation, gas-phase thermochemical conversion (such as Fischer-Tropsch or syngas to

[1] UNICA, rough estimate due to volatility of Brazilian currency

methanol/ethanol chemical catalysis), direct to liquid thermochemical conversion, transesterification of oils, and solar to fuel precursors such as algae. In my opinion solar fuels like algae, Fischer Tropsch, syngas to methanol/ethanol chemical catalysis, plant oil based biodiesel (like soya bean/canola) and even enzymatic hydrolysis of cellulose are unlikely to be economic in the near to mid-term. Even newly fashionable plant oil based methods (like jatropha or camelina) will not scale adequately due to their low yield per acre (200 to 300 gallon per acre). Meanwhile, Palm oil based biodiesel is an environmental disaster. Chemical catalytic processes like Virent are also less promising. Some new efforts, like Synthetic Genomics, could be promising in the long term (ten years or more) if they can overcome genetic engineering environmental risks in large-scale systems. Other processes based on waste fat and organic matter from animal husbandry operations or used restaurant grease, may be economic but are too unscalable to be material. I expect that the much touted enzymatic hydrolysis cellulosic ethanol technologies using enzymes from companies like Novazymes and Danisco will also fail to be economic, and companies like Mascoma that use that approach will likely need to switch to cellulosic sugars from companies like HCL Cleantech.

So what will work? The early best answers in my opinion, based on operating costs, flexibility and scalability are sugar and gas-phase fermentation for specialty molecules, and direct-to-liquid thermochemical conversion for fuels. The fermentation pathways are excellent for producing specific chemicals and custom-designed hydrocarbons (sugars: Gevo, Amyris, LS9, Solazyme; gas-phase: LanzaTech, Coskata), and can thrive in high value markets that offer tens of multi-billion dollar markets. Some generic fermentation technologies that go after fuels directly will struggle with costs. The sugar fermentation pathways will have to wait for low cost cellulosic sugar technologies like the one HCL Cleantech is developing and a few years of experience with yield and cost optimization to go after the larger scale fuels markets. Direct-to-liquid thermochemical conversion that yields a crude oil or diesel and gasoline blendstock, represented by the novel approach of Kior, are nearer term candidates for economic viability and appear to be much lower risk technologies that can globally (read unsubsidized) compete near term with oil at today's $90 per barrel price and in the mid-term at prices as low as $60 per barrel. Cellulosic ethanol and chemicals technologies like Coskata and Lanzatech can out-compete corn ethanol if they can finance their first commercial facility to prove their economics. These syngas-based gasification technologies will be substantially superior and higher yielding than traditional Fischer Topsch technologies and have the advantage of pursuing multiple high-value chemical markets in addition to the fuel ethanol market. They will suffer from high capital costs (if they must build the front-end gasifier) but will have low operating costs and good rates of return on the capital if they can be built. Technologies like Range that started with chemical catalysis will need to switch over to these newer fermentation technologies.

Though sugar fermentation is a powerful production method, I personally don't believe that food-based sugar fermentation technologies can scale adequately to meet fuel demands. However, the sugars need not be food-based; there are several competing enabling technologies that take cellulosic biomass and convert it via hydrolysis to sugars that are pure enough for fermentation. HCL Cleantech hopes to be able to deliver $0.08 to $0.12 per pound sugar, quite competitive given the price range of mostly 10 to

25 cents per pound for the last five years.[2] This type of technology unshackles sugar fermentation processes from the negative perception of the food vs. fuel-debate, and delivers more diverse, lower cost, and scalable feedstock sources, with lower price volatility. Regardless of the technology, feedstock costs will be critical. For instance, I believe prices for woody biomass and agricultural waste, which are in the $50 to $65 per ton range in the US, will drop within a decade as the biomass crops, agronomy and logistics ecosystem evolves, more competition develops and yields improve. Substantially lower prices are available internationally.

The key issues to focus on in determining a good biofuels technology are the upfront capital costs, ongoing operating costs, and environmental impact (mostly based on feedstock and location). Looking at any individual company, beyond the technology, it is additionally important to consider the proposed business model, the tactics for "boot-up" or getting the first commercial facility going, and the regulations and incentives in place. A company must find economic markets for its first commercial facility, be they in fuels or specialty chemicals, to get down the learning curve and start reducing its costs. This critical step is often difficult in an otherwise promising story. Non-oil related markets (such as nutraceuticals for algae) are unlikely to lead to economics that work in the fuel market. In addition, in order to avoid abuse of the terms "renewable and sustainable" to a minimum, we need to institute a comprehensive carbon, land, air and water impact assessment metric (one I call a CLAW Rating upon which I've written previously) for each biofuel. Not all biofuels are good biofuels.

In the current market, it can be difficult to secure capital in any sector. Therefore, biofuel companies able to deploy a commercial, cash flow positive plant for under ~$100 million have a distinct advantage. Some companies can achieve this with greenfield plants (e.g., Kior), but others are employing clever business models; LanzaTech's first few projects use the waste gases of a steel mill in place of a capital intensive gasifier, to feed their fermentation. Gevo is retrofitting existing corn ethanol facilities for high efficiency butanol production for chemicals markets. Amyris and LS9 are bolting their technology onto working sugar mills in Brazil. In contrast, a commercial FT facility would be on the order of several hundred million. Once you've got a plant up and running, the operating costs are dependent on feedstock costs, energy, chemicals, water handling and personnel. Given the importance of feedstock costs, yield is a critical parameter. Of course, to enter the high value chemicals market, a higher cost per barrel of oil equivalent is acceptable; but to expand markets the key is to have a path to much lower costs. Keep in mind that if the process hasn't been demonstrated at 100,000 gallon per year scale, the accuracy of the cost estimate, be they capital or operating costs, is, at best, a guess. Meanwhile, some licensing models are unlikely to be profitable. A licensing deal can create structures that often lead to long delays due to the risk averse partner, with fewer technology iterations and lower financial upside even if they succeed. That said, licensing within large markets can make sense provided it is structured such that the licensee cannot limit the startup's potential to grow in the future. In our portfolio, only Verenium, in my view the weakest of our cellulosic companies, entered a licensing agreement. Shell actually offered a relationship to LS9, which we declined because they asked for a license to the technology.

[2] http://www.ers.usda.gov/Briefing/Sugar/Data.htm

There are those who question the availability of sufficient land for fuels. Indeed, using extrapolations based on corn ethanol, there clearly isn't enough land. However, if we apply some creativity, and consider other processes and sources of land, a very different picture emerges. Forest waste and currently shutdown paper mills in the US can produce enough woody material to meet our goal of 22 billion gallons of advanced biofuels by 2022 without any material land impact. Abandoned lands alone (385 to 472 million hectares, or 950 million to 1.2 billion acres globally)[3] could yield (at current acreage yield averaging only 5 tons/acre) over 30 percent of world oil demand according to a recent paper[2]. Per another study, which includes grassland, savanna and shrubland suitable for low-input high-diversity mixtures of native perennials, total land availability jumps to over 1.1 to 1.4 Billion hectares, with the potential to address up to 55 percent of our liquid fuel demands if suitable current generation energy crops are planted.[4] Yields of much of this land could easily be improved by many multiples (700 percent increase in productivity has happened in corn in the last fifty years) with specialty energy crops, though that will take time to engineer. In fact, development of high yield polycultures, most non-food perennials and winter cover crops is essentially unexplored. There is a lot of room to improve yields, while decreasing environmental impact by minimizing/eliminating fertilizer and water use, tilling and other agronomic practices.

Many biofuels technologies have made significant progress over the last few years; there have been some surprises, some partnerships and some clear winners and losers. Some have failed for genuine technology reasons, but many others for business reasons, market/investor or regulatory biases. Many technologies are as yet unclear and some seem to be promising. There are many positive surprises to come. However, we believe that cellulosic feedstock, regardless of the processing technology and end-product, is the likely winner at scale in the fuels market. Sugars will work in the chemicals market. I would bet on technology where the first instantiation is somewhat competitive in at least one market (like many of the new sugar fermentation hydrocarbon or new molecule technologies and the direct to liquid technologies) that gives the base technology an opportunity to improve from a production platform. I would bet against technologies like Fischer Tropsch that have been optimized for a long time and have little additional room for progress in yields or costs.

Over the last few years the industry has seen a tremendous number of strategic and technical iterations coupled with new discoveries. Novel business plans have been developed, to exploit capital-light opportunities, as well as to branch out into high-value specialty chemicals sector. It is critical to continue nurturing the next generation biofuel landscape; there is enough "there" there to warrant continued investment. The winners will be big winners, and some of "losers" in the fuels market will still be able to find reasonable sized niche markets such as billion dollar specialty solvent markets – the so called Wall Street "bear case" for a company. We should also expect new developments currently unanticipated by me, which will surprise many of us in both positive and negative ways. Four years ago I would have expected a 70 to 90 percent failure rate in our biofuels portfolio. Today I expect more than 50 percent of our technology bets will be successful.

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[3] The Global Potential of Bioenergy on Abandoned Agriculture Lands, J. Campbell et all Enviro Sci Tech, 2008
[4] Land Availability for Biofuel Production; X. Cai et al, Enviro Sci Tech 2011

Within 5 to 10 years at least half a dozen technologies will be competitive even with $60 per barrel oil, with some more profitable than others. The critical point is that for the next 10 years at least, there will be unbounded demand for biofuels and biochemicals. The quantities required by the current regulatory mandate in the US will be an achievable stretch with all the technological innovation. US and worldwide demand of oil will be such that biofuels will not compete with each other, they all compete directly with oil. Each technology is suited to specific local conditions, and with the expected demand, there is ample opportunity for all these and even more technologies. By 2022, advanced biofuels will become material in the oil supply equation, and will be a significant market force within twenty years. I firmly believe that in 30 years, the price of oil will be more dependent on the marginal cost of non-food land than anything to do with exploration, drilling, OPEC, or Middle East instability. If my expectations on technology come true and financing and regulatory support is made available for the infancy stage of biofuels, I expect biofuels will drive the real price of oil to $30 to $50 per barrel in 2010 dollars by 2030!

Part 1: Production technologies: where are we?

The financial crisis of 2008 set back a number of projects and slowed actual construction of pilot and demo plants like it did in all industries be they biofuels or traditional fossil energy projects. That coupled with the negative press for corn ethanol slowed progress and funding of biofuels to a crawl, causing delays of up to two years in many business plans. But despite these challenges, entrepreneurs have persevered and in many cases are further along than expected in achieving practical economics that now justify their first commercial units (FCUs). FCUs are particularly hard to fund given that they are first of a kind technology, and there is now a risk averse capital funding environment. Further, FCUs are generally of smaller size than the optimal scale commercial plant, are not "value engineered" (the goal of the FCU should be, in my view, cash breakeven or better and proof of technology, not cost optimization), and hence their output suffers from more challenging economics in commodity product markets. Hence, some companies like Amyris, Gevo and LS9 have targeted higher value specialty products to commercialize, until yields improve, scale increases and costs and capital raising risks decline. By starting with high value products and going to progressively lower value (per gallon) markets the addressable market size will continually expand for these companies, eventually hopefully encompassing most of the fuels market - among the lowest price per gallon markets. Some like Coskata and Lanzatech (and others) are developing multi-product technologies, which gives them optionality. Others like Kior have gone directly into fuels because of their technology, supply chain compatibility and current production costs which can be competitive with fossil oil. Below is a rough summary of the major technology pathways and our current comments on them. We reserve the right to change them as we learn more or the technologies progress, in fact this progression of views and the emergence of other new technologies is expected. Over the last two years I have been pleasantly surprised at the progress in direct to hydrocarbon renewable fuels. Finally, there are efforts that are too early in their development to characterize such as Synthetic Genomics, Virent, Codexis, electro-fuels, etc to estimate with any reliability and others for which not enough information is available to us.

Incidentally, given the amount of R&D that is now done in private companies that don't publish their results, I find knowledge of status among academics to be relatively out of date too. Unfortunately a somewhat unreliable rumor mill appears to be the best balance of reliable/current information along with informed projections of technology pathways' potential.

Table 1 summarizes the major technology pathways (leaving out the currently commercial starch/sugar to ethanol processes; bolded companies are part of Khosla Ventures Portfolio).

Table 1:

Pathway	Feedstock	Outputs	Examples	Comments	FCU (minimum size cash flow positive facility)[5]
Liquid fermentation	Sugars (e.g., corn, sugar	Highly controlled, single chemical	**LS9, Gevo, Amyris**,	Suitable for specialty chemicals and specialty	Retrofits/bolt-ons costing $40-100M

[5] Rough estimates, very little public information available, some facility costs are full commercial scale vs. FCU

to higher alcohols, hydrocarbons and esters	cane, hydrolysis sugars from cellulosic feedstocks)	output, pathway dependent (e.g., iso-butanol, FAME, Esters, lipids, Farnesene) Fuels are less likely to be economic if they need significant post-processing. Direct production of fuel blends like butanol or FAME may allow for earlier entry into fuels. Costs are less critical for chemicals.	Solazyme	fuels (e.g., jet). Starting to build first commercial units: target 2012 to 2013. Need to reach commercial yields at demo, and test 2,000 gallon tank scale to prove economics or 100,000 gallon per year facility scale to have reliable data; many do; various chemical outputs give them options.	to cash flow facility. Varies widely, but small $ allows low risk bootup. Companies that require new facilities will have difficulty booting up unless facility is really low cost
Liquid fermentation of cellulosic feedstocks to ethanol	Sugars via hydrolysis of cellulosic material (described below)	Ethanol	**Mascoma, Verenium,** Qteros, **(**Novozymes, Danisco)	Enzymatic processes such as Novozymes are unlikely to be competitive. Cheap cellulosic sugars may help enable these pathways. In Mascoma's case, use of CBP (consolidated bioprocessing) helps alleviate the high cost of enzymes and may have lowest cost in this class but none are economic yet	$175M-300M
Gas fermentation	Steel/Coal waste gas; syngas from biomass or coal	Highly controlled, single or multi chemical output (e.g., ethanol, 2,3-Butanediol, & other specialty chemicals)	**Lanzatech, Coskata,** Ineos	High capex for biomass, but low opex; low capex & opex for waste gases; suitable for ethanol, more upside in chemicals; FCU in 2012 to 2013	$4-500M for commercial plant with biomass gasification including fermentation; $50-100M for backend waste gas conversion
Catalyzed thermo-chemical cracking	Lignocellulosic biomass, all types, from wood whole logs, ag & wood wastes, algae etc.	Relatively easy "drop-in" renewable crude oil. With hydrotreating, can produce fuel blendstock	**KiOR**	Scalable process, familiar to oil industry. Similar supply chain and uses, FCU operational in 2011 to 2012; likely to be competitive unsubsidized near term at $80 oil; high value distillates	$75-125M
Solar fuels	Waste water, CO2 + sunlight	Lipids that can be converted to biodiesel (FAME, green diesel, jet fuel or other), or	Sapphire, Cellana, Aurora Algae,	No clear near term path to economic viability. High theoretical yields per acre (>4,000 gallons per acre),	Hundreds of millions(?)

		nutraceuticals	General Atomics, Petro algae	but not proven. Pilot and demonstration scale. We are skeptical of economics in this category; larger environmental risk for GMO open pond organisms	
Natural oil hydro-treatment to produce hydrocarbons	Natural oils and fats (palm, vegetable, animal fat etc)	Hydrocarbon fuels	Dynamic Fuels	Limited scalability due to feedstock	~$100-150M
Pyrolysis oil hydro-treatment to produce hydrocarbons	Wood chips and wood waste	Hydrocarbon fuels	UOP/Ensyn, Neste	Significant hydro-treating required due to high oxygen content to produce hydrocarbons	~$100-200M(?)
Transesterification of vegetable oils, animal fats	Natural oils and fats (palm, vegetable, animal etc)	Biodiesel		Limited scalability. Often food based and likely less economic. Land use concerns due to low yield	
Gasification with thermochemical conversion to ethanol, methanol and hydrocarbons	Cellulose/ hemicellulose/lignin	Syngas for fermentation, or for chemical catalysis conversion to ethanol, methanol, or Fischer Tropsch to hydrocarbons	Choren, Rentech, **Range**	Chemical catalysis for ethanol and Fischer Tropsch likely uneconomic. High capex, high opex.	Hundreds of millions
Liquid Catalytic conversion of sugars to hydrocarbons	Sugars (e.g., corn, sugar cane, hydrolysis sugars from cellulosic feedstocks)	Hydrocarbon fuels	Virent	Limited information available, clean sugars and hydrogen appear required for good outputs. I am somewhat skeptical but have to admit less than full knowledge of details	unknown

Table 2: (cellulose to fermentable sugars)

Acid (Concentrated HCl) hydrolysis	Biomass Cellulose/ hemicellulose	Sugars for fermentations	**HCl**	Potential for integration or retrofits pulp and paper mills, and increased productivity of renewable chemicals and non-food sugars. Changes scalability of sugar fermentation processes.	$35-40M for FCU; $180-200 M for optimal commercial plant
Enzymatic hydrolysis	Biomass Cellulose/ hemicellulose	Sugars for fermentation	Novozymes (front-end), Danisco	Potential for retrofits for corn & sugar ethanol plants, does not appear economic near term;	

				Mascoma CBP reduces cost by reducing process steps but not yet economic.	

There are dozens of companies all taking different approaches, and vying for different markets. Some technologies, like Gevo, LS9 and Amyris, focus on creating a single molecule, whereas other technologies, such as Kior, create a diverse mix of chemistries (much like crude oil has) but at lower cost that can be blended with crude oil and dropped directly into a refinery or if hydrotreated can be used as gasoline or diesel blendstock. These processes result in a range of production costs, many of which will be acceptable, depending on the end-products. For example, thermochemical processes which yield mixtures of chemistries (such as crude replacements) should aim for costs below $20 to 25 per barrel of oil equivalent (BOE) (ex-feedstock costs including 15% IRR on capital investments) and be market competitive within 5-7 years of their launch (without subsidies). Biology-based pathways that create precise molecules can afford more expensive production processes and feedstocks due to the ability to tune the end-products and target higher value chemicals segments with higher price points. In many instances product separation/ purification or post processing is a critical cost factor. In the long run, fuel processes must use low cost non-food feedstocks (for scalability and cost) and high yield low cost production processes, have minimal post-process steps to get to marketable product, or produce a valuable co-product (it's important that the market for this co-product is of similar size to the main product, or else it won't scale). For high value chemicals, these issues are less critical due to lower cost sensitivity. Some processes, like those of Synthetic Genomics, are early enough to be difficult to assess viability in my view, though they appear to carry significant environmental risk (much like the GMO controversy) if used in open ponds or open ocean. In bioreactors, most algae based processes carry high capital cost risks. Other processes like Virent, Qteros, Joule and numerous others are less well known to me.

Below are the major technologies in more detail:

Sugar Fermentation: Regardless of the carbohydrate source, a conventional yeast fermenting sugar to ethanol already operates at the highest carbon yield theoretically possible in corn ethanol plants – i.e. 4 out of the 6 carbon atoms from a glucose molecule – and much of the energy - end up in a molecule reduced enough to burn in a combustion engine. For example, at theoretical yield glucose is converted into two 2-carbon ethanol molecules, or one 4-carbon isobutanol molecule, or four carbons of a multi-carbon hydrocarbon molecule. Without the input of carbon-free energy, it is theoretically not possible to improve upon this yield. Ethanol plants are able to operate at these yields in part because the yeast function without oxygen – i.e. anaerobically. Some biological processes and end-products require oxygen – i.e. are aerobic - which can limit yield as the cells "burn" additional carbohydrate feed stock to provide the cell with energy. Generally anaerobic or near-anaerobic/ micro-aerobic fermentation technologies can approach the maximum theoretical yield and make the most efficient use of any given feed stock. However, anaerobic processes have their own drawbacks and limitations; anaerobic processes tend to achieve lower growth rates in certain conditions (which leads to higher capex), and there are several high energy molecules that are not possible to directly synthesize through anaerobic pathways. In the end, the goal is to get to a product of commerce the lowest cost way possible. Depending on the product, one can either take an entirely biological route, or a mixture of biology and chemistry.

Because ethanol plants already operate at high carbon efficiency on the available feed stocks, it is reasonable to compare new technologies to these existing plants as one metric to gauge their performance. A typical ethanol fermentation continuously produces ethanol at the rate of 2 to 3 grams of ethanol per liter of broth per hour at 90 to 95 percent theoretical yield. These plants are fairly low tech and inexpensive to build - essentially they are just large vessels with simple distillation equipment (though distillation can be energy intensive and expensive)– yet still have capital costs of about $2 to 3 per gallon of annual capacity. If a new process can operate anaerobically, the capital and operating costs of that plant will be directly proportional to the performance of the new process verses ethanol production, e.g. if the production rate is half that of ethanol, capital costs are roughly doubled. If a new process requires oxygen, additional capital and operating costs will be required for to deal with mass transfer issues, compressors, gas handling, and safety concerns. There are also micro-aerobic processes. New carbohydrate feedstocks, especially sugars derived from energy crops, may require additional capital, but will reduce feedstock costs.

In most processes, the cost of feedstock is the primary contributor to the cost of production. Some processes can tolerate a wide variety of sugar types and purities, others can't, still others can tolerate complicated mixtures (like dry mash ethanol), others require pure sugar feedstocks in order to minimize separation costs, or to make the separation of the product even possible. In determining the lowest cost route to a given product, one must consider the whole of the business system and production processes from raw material to finished commercial product. Separation, post-processing, purity of feedstock (Virent, rumor has it, requires very pure and hence expensive sugars to preserve catalytic efficiency in their thermochemical route) and feedstock costs are additional significant considerations. Each process requires a different quality or purity of feedstocks, and hence feedstock costs can vary even within the same technology category. Gevo for instance is able to use starch directly, and their organisms can tolerate a high level of impurities. Meanwhile, HCL CleanTech's extraction oriented approach to making sugars appears to provide sugar feedstocks of higher purity than those coming from traditional corn or sugar cane sources, and could be significant for the long-term competitiveness of sugar fermentation platforms. In addition to using yeast and bacteria, there are companies that produce various chemicals from microalgae by fermentation, using sugars, such as Martek and Solazyme. Thus the algae in this case are just another conversion engine similar to yeast or bacteria (as opposed to what many people think of as algae which converts solar energy to lipids), by transforming sugars to fuels and chemicals. Their near-term business models are for higher value products and biofuels. The rate of yield and productivity improvements should be similar to other single-celled organisms (like e. coli and yeast), though microalgae does not have as extensive a molecular tool kit for optimization as these other two organisms

One often expensive part of fermentation production process, and any other biological approach, is the separation of the final product from the fermentation broth; for example, most algae projects face this substantial challenge. Distillation and even centrifugation are often used, which is relatively expensive. Some companies have succeeded in engineering organisms to secrete the chemicals (e.g., LS9, Amyris), which then phase separate, enabling cheaper separation. Others like Gevo have developed proprietary low cost, low energy separation techniques. Several companies are developing the capability to convert the fermentation product into a wide variety of chemicals and fuel end-products, though each step generally adds additional expense and yield reduction. Direct single-step production can be especially important in cost sensitive markets like fuels.

Gas-phase technology: Cellulosic feedstocks can be gasified and either thermochemically processed or used as a fermentation feedstock for fuels and chemicals. Capital costs for purely thermochemical technologies are much higher than 1st generation corn ethanol plants, but these plants are typically powered by the equivalent of the non-carbohydrate portion of the biomass feedstock, which reduce operating costs to make total costs cheaper than corn ethanol. Bio-fermentation is currently the most promising backend to syngas production, because it can co-produce precise chemistries and hence high value chemicals and cheaper fuels than chemical catalysis, and operate cost-efficiently and with higher target molecule yields. The big challenge here is the capex for the gasification front-end, which can be anywhere from $4 to $6 per gallon (ethanol equivalent) or more of yearly capacity but one gets the advantage of much lower opex. The economics should work well for ethanol production (where the benchmark should be corn ethanol production costs – the cash costs for this approach should be substantially cheaper than for corn ethanol, but the economics get even better when specialty chemicals are produced using this approach. Product flexibility of the facility may be another factor that could be engineered into the design to offer lower risks for the capex. As a result of this, some gasification and fermentation companies have considered partnering, to marry efficient gasification and fuel production technologies. Lanzatech has cut out the front end by planning to bolt-on to already existing sources of raw waste gases (from steel mills and coal plants or any source that includes carbon monoxide and/or hydrogen), dropping capex substantially, with low opex. They can use biomass gasifiers as well to produce the syngas as feedstock for their process. In any biological process, bug productivity is important and sometimes challenging to maintain. Many companies maintain redundant feed streams, seed reactors, and advanced monitoring and control of any inhibitory molecules, to assure continuous productivity. In our view, the traditional path of chemical catalysis of syngas to fuels, (be it ethanol or Fischer Tropsch (FT) synthesis), appear economically challenging. FT is generally the domain of old style thinking. It is sometimes used as a code word for coal to liquids, which does not chart a sustainable path. Besides, we believe bio-fermentation of any type of syngas is the most cost-effective approach; most FT advocates are simply not up to date on the day-to-day developments in the leading startups.

Direct to liquid thermochemical technology: A second thermochemical route, which Kior takes, processes solid biomass direct to liquids, while catalytically removing oxygen. Their unique approach employs a FCC-like (Fluid Catalytic Cracking) process from the oil refinery world with a special catalyst for cellulosic materials. The input is woody biomass, corn stover, sugar cane bagasse, or any other cellulosic/hemicellulosic/lignin material. The catalytic process occurs for a few seconds at moderate temperatures and pressures. The result is a low oxygen renewable crude oil (the same way nature makes crude oil from biomass but takes millions of years to process), as well as some natural gas. The oil yield is nearly 1.5barrels per dry ton today and with the potential to rise to 2 barrels per dry ton. Unlike sugar hydrolysis and fermentation technologies, Kior can convert all parts of the biomass, including lignin, without the need for separation. That capability will likely result in the highest transportation fuel yields per ton of biomass. In contrast to ethanol, their product looks and behaves like a high value crude oil, or a diesel/gasoline blendstock after hydrotreating –superior to traditional biodiesel and superior to typical US crude oils because of its higher value fuel distillate fractions and lack of sulfur. Kior initially intends to sell a diesel and gasoline blendstock. Kior currently has a 15 barrel per day demonstration plant running, and has just started construction on its first commercial-scale unit in Mississippi. The oil industry is familiar with the basic FCC process, which should result in easier acceptance. Scalability for FCC processes is also well understood and broadly characterized. Additionally, since the Kior oil is stable and miscible in most crude oils, no new infrastructure is required, and supply chain planning and logistics should be simplified for refineries. Cashflow positive facilities are small scale, requiring less than $100 million to be economic scale. Most of the associated jobs created are rural: not only in agriculture like other biofuels, but also in forestry and transportation. This, along with energy security, are critical issues for any fuel attempting to gain political and business support anywhere in the world. Familiarity to the oil industry and hence the ability to assess, characterize and help scale it is also a major consideration, and will make capital formation easier. This approach should be distinguished from pyrolysis oil production – a very different process.

Solar to fuels (Algae)

Microalgae-based processes pose several challenges. Enclosed culture systems (tubes, panels, bags – generically photobioreactors or PBRs), cannot be scaled-up and have high operating and capital costs, hundreds of dollars per square meter (versus under $1 per square meter for farming). PBRs have had limited commercial success even for very high value ($>10,000 per ton) nutritional supplements. Essentially all commercial production for such microalgal products uses open ponds, mostly raceway-type with paddle wheel mixing. But even the costs of such simple ponds are too high for commodities, whether feeds or fuels, due in part to the relatively small scale of current production systems and in part to the small markets for these high value algae products. Engineering designs and techno-economic analyses suggest that much lower cost systems could be built and operated, if pond designs are simplified (e.g. earthen ponds), scales increased (to 10 acre ponds, vs. about 1 acre now) and low-cost harvesting process developed. However, even then, production of algal feeds and fuels would require achieving very high productivities, nearly 50 tons per acre and a high oil output, about 4,000 gallons per acre. Although high productivities are possible in principle and routinely forecast, being one of the main attractions of microalgae biofuels, they still remain undemonstrated continuously at scale, and will require considerable long-term R&D. This is to say nothing of such problems of how to actually stably cultivate and cheaply harvest the algae. General Atomics currently has a project with DARPA in Hawaii to build a 1,000 acre raceway for fuels production; this will be an interesting test case, but I am skeptical.

Thus, I view that solar algae biofuels still need a great deal of R&D and likely are ten years out, which I do not see as attractive for a venture investment. As for the case for fermentation processes, the path from the current high cost of commercial production to biofuels most likely will pass through intermediate stages of scale and value, such as specialty animal feeds priced at $1,000 to 2,000 per ton and with markets in the hundreds of millions of dollars. Many claim that a major benefit for microalgae, that they can use the CO2 in flue gases from power plants. I dismiss this out of hand: it makes no difference whether the CO2 comes from air, as for crops and trees, or from a power plant, as for algae, except that air CO2 is free, and sustainable. The algae doesn't "sequester" the CO2 (or limit CO2), as its source is still a fossil fuel and its destination (as a fuel) is still the atmosphere. One near-term application of micro algae is in wastewater treatment, and there the algal biomass can only be used for biofuels. But these would be relatively small, dispersed, facilities, and any venture in this space requires a business model to capture value from the development of such technology. The idea that co-production of algae fuels and nutraceuticals would improve the economics is a difficult one to defend. Though co-products are valuable, the scale of nutraceuticals is much smaller than fuels.

Before leaving algae, I must also mention seaweed; also algae, but macro- not micro-algae, which are getting some interest in Asia and Europe. DOE ARPA-E recently funded a JV of Dupont with a start-up, Bioarchitecture Lab, in California, to produce biobutanol from seaweeds. A very challenging concept, and in very early days, but that is what ARPA-E is about; I will keep watching.

Other technologies

There are also a few technologies that are "too early to tell." One set of examples are so-called "electrofuels." ARPA-E just supported 13 projects with small grants, which use electricity, hydrogen or ammonia as an electron source to drive fuels production. The idea is to harness new microbe pathways to form fuel molecules of various types, using only electricity, CO2 and sometimes water as an input. These efforts are extremely early, and may yield something ground-breaking. Still, the source of the electricity matters and much of ours is still from coal (and our hydrogen is from natural gas).

Considerations for companies and technologies: There are several factors which affect the attractiveness of any biofuels technology:

Environmental factors/policy –Any successful biofuel should have a life cycle analysis significantly better than petroleum (RFS II requires 20 percent improvement over gasoline for new renewable fuels processes (corn based), and 50 to 60 percent for advanced biofuels, cellulosic biofuels and biomass-based diesel[6]), though national security is a big enough reason alone to pursue biofuels. In my view, a

[6] http://www.epa.gov/oms/renewablefuels/420f10007.htm

technology and its input feedstocks should have at least 50 percent carbon reduction initially to have a shot at 80% reduction as the process and supply chain matures.

Three standards of Advanced Biofuels

Biomass-Based Diesel: 1 billion gallons by 2012 and beyond

- E.g., Biodiesel, "renewable diesel" if **not co-processed** with petroleum
- Must meet a **50 percent** lifecycle GHG threshold

Cellulosic Biofuel: 16 billion gallons by 2022

- E.g., cellulosic ethanol, BTL diesel, green gasoline, etc.
- Renewable fuel produced from cellulose, hemicellulose, lignin or **algae**
- Must meet a **60 percent** lifecycle GHG threshold

Unspecified Advanced Biofuel: Minimum of 4 billion gallons by 2022

- Essentially anything but corn starch ethanol
- Includes cellulosic biofuels and biomass-based diesel
- Must meet a **50 percent** lifecycle GHG threshold

Renewable Biofuel: **Up to 15 billion gallons of "Other Biofuels"**

- Ethanol derived from corn starch – or any other qualifying renewable fuel
- Must meet **20 percent** lifecycle GHG threshold - if produced in new facilities
- **Existing** biofuels facilities not required to meet conventional GHG threshold

Section 526 of the Energy Independence and Security Act (EISA) 2007 is a major driver for operational purchases of biofuels for the Federal government. In short, it says that any alternative fuel the government purchases, must have a lifecycle greenhouse gas emissions profile equal to or less than petroleum. Fuels that meet EPA's RFS2 standard will comply, but so too will other feedstock/ fuel processes. I believe a CLAW framework as I have proposed previously would be ideal for measuring the environmental impact of biofuels beyond just their carbon footprint. CLAW stands for Carbon emissions, Land use, Air pollution and Water use rating, and should be used to assess each new and currently operating plant individually. I have written about this in an earlier paper in detail,[7] and frankly it should be applied to any new technology, not just biofuels. Without an accurate and holistic assessment of carbon emissions, land use impacts, air pollution and net water usage, the true impact of a new technology is difficult to measure. The Roundtable for Sustainable Biofuels, based out of Switzerland, is

[7] http://www.khoslaventures.com/presentations/WhereWillBiomassComeFrom.doc

currently drafting a potential system. In the absence of such a standardized rating system these factors should be qualitatively assessed, hopefully by industry analysts. The individual monitoring and assessment of each facility is critical, because general ratings based on a technology platform will result in abuse. A technology could be environmentally beneficial in one place while quite destructive elsewhere, due to implementation or simply environmental variation. Indirect land use calculations are complex though I believe the California "low carbon fuels standard" is a reasonable start to the effort of characterizing lifecycle carbon emissions of each technology. I recommend this approach to other jurisdictions. Water use should be measured against the water used in producing and refining a gallon of gasoline or diesel. Thermochemical processes will, I suspect, do substantially better than fermentation technologies and even fossil oil production/refining technologies on water use. Water use even among fermentation technologies can vary widely. I suspect that the majority of feedstock cultivation for biofuels over time will go to rain fed non-food agriculture and forestry. Another important aspect to consider is the production of unwanted byproducts, vs. useful byproducts. As an example, some biodiesel processes produce glycerin, which is currently in oversupply. Definitions of good vs. bad byproducts are malleable, as unexpected technologies may be created to usefully consume whatever byproducts are created.

Ability to scale economically– There are several factors that affect a company's ability to scale quickly. It would be naïve to believe that Government regulations do not play a role. In addition to the team's experience, and the ability of the feedstock to scale, which I will cover later, one needs to consider feedstock fungibility, the nature of plant manufacturing, the ability to build exact replicates, centralized plant control, personnel training, and many other factors. Processes that can support multiple types of feedstocks, such as the gasification and thermochemical processes will have a huge advantage as initial feedstocks like wood chips or bagasse can be supplemented by forestry waste (whole logs, tree bark, leaves and branches, the 30 to 50 percent of product that goes waste in hardwood processing, sugarcane field waste and potentially bagasse, agricultural waste like corn stover or corn cobs etc.), all of which will improve scalability and reduce feedstock costs over time, as well as improve feedstock price stability. These feedstocks also offer significant upside as the harvesting ecosystem for such peripheral biomass is developed by the likes of John Deere and Caterpillar, and will enjoy declining costs. The development of productive polycultures and perennials may also play a big role in net positive impact from feedstock cultivation. Personally, for fuels applications, I might avoid sugar based fuels technologies until such time that HCL like acid (non-enzymatic) hydrolysis of biomass technologies become available, for scalability and price volatility reasons. Still, sugar will likely remain as a source for non-fuel renewable chemicals. Different technologies are on very different cost trajectories due to their capital structure, materials, technology maturity and the ecosystem being built around their feedstocks. Current costs are not always a good predictor of future costs, and cost trajectories that rely on eeking out the last few percentage points from 90 percent of theoretical yield mature technology are much harder to realize than those that aim are improving from 50 percent efficiency, as an example.

Regulations/certification

New fuel molecules require EPA approval, though there are a long list of registered fuel additives for diesel and gasoline. Even drop-in molecules require testing and qualification, but those tests are much less onerous compared to those trying to introduce new molecules. Ultimately, large differences exist in time to market of new fuels molecules. There are extensive Tier 1 (combustion emissions for known molecules) and Tier 2 (extensive toxicology work for new molecules) tests required for approval. Hydrocarbons that are already in existing conventional fuels will likely be easily registered – unless there are biologically active compounds still included, like hormones, etc. As a result, process impurities need to be closely monitored. It is necessary for molecules to meet existing ASTM specifications (or go through a process of developing a new spec) to be sold as fuels. ASTM specifications for blend stocks and final fuel blends must be completed, and continued participation is required to keep specifications current with constantly changing conventional fuel specifications. As an example, Gevo has registered their isobutanol as a gasoline additive. Meanwhile, Amyris attained EPA approval with Farnesane to blend up to 35 percent with ultra-low sulfur diesel, and LS9's fuel product is registered as a biodiesel. Several companies have yet to register or complete tests on their fuels. Jet fuel has a formal process in place for certifying new fuels, while gasoline blend stocks and diesel have ASTM specifications. A more expansive engine-testing program to ensure thorough and quick assessments is highly desirable. It appears that new molecules for jet fuels are likely to have the longest approval cycles. These regulatory issues take time, but are not necessarily high risk in most cases.

Additional approval is required to meet the RFS II standard described above, as well as the low carbon fuel standard in California – where fuels must fall below the reference for gasoline, the latter includes a controversial indirect land-use impact estimate. In some countries GMO organisms need special consideration for biological processes and may be particularly problematic for some GMO algae approaches if the algae are grown in open ponds or open oceans.

FDA/USDA approval for co-product use as animal feed is required. Most yeast should face lower barriers, depending on country specific GMO regulations. As a result, knowledge of country-specific GMO issues is necessary. Approval of organisms as Amyris has done in Brazil is an example of a good approach.

Fungibility or "Drop-in" features:

It is best when a new fuel functions in the existing fuel infrastructure, though ethanol is getting enough infrastructure to be viable in some parts of the US. If the technology has multi-product, multi-market and multi-feedstock capability, it has a lot higher possibility of success. Ideal fuels are compatible with existing pipelines, storage tanks, trucks, trains, and barges. These fuels should also be compatible with fuel pumps at gas stations and with engines. Finally, it is good if they are compatible with conventional additives used in fuel systems – anti-oxidants, anti-corrosives, drag reducing agents in pipelines, etc. Some molecules are considered conditionally drop-in, for instance FAME, which works best as a diesel drop-in in warmer climates, but is not suitable for cold weather or winter due to poor cold weather characteristics. In the end, new molecules will require extensive data sets before they're integrated into the existing infrastructure. Given that ethanol has gained relative acceptance and reasonable infrastructure, the next new molecule (or family of molecules), unless it is very similar to hydrocarbons or ethanol, will face a bigger hurdle to acceptance. Most common hydrocarbons, on the other hand, will have relatively low risk acceptance as they are well characterized. Drop-in products will have easier access to markets. Though many pathways can ultimately produce drop-in fuels with post-fermentation processing, the more unit operations required to go from the fermentation product to the final product, in general, the higher the cost.

Tactics for "Boot-up"

The transportation fuel market is over 14 million barrels per day in the US alone, across diesel, gasoline and jet fuel. Economies of scale (and relationships with refiners with these unit operations and logistics for moving products) are not easily achieved until operating at significant scale. So companies need to have a startup strategy to "boot-up to scale" where costs/experience mature, be it through finding niche markets (DOD jet fuel contract, drop-in chemical or fuel, meeting a regulatory need, etc.) producing accepted blendstock and meeting customers' regulatory requirements. Ethanol production is ~12 billion gallons per year and infrastructure is gradually being adapted to accommodate it, as production from cellulosic feedstock is expected to dramatically increase this amount. Some companies can mitigate the startup risks; in their S-1, Amyris identified a $15 billion chemicals market which can be addressed competitively with their technology in its current state. As a result, they have an extremely large addressable market to focus on in the meantime, while they scale up and go through regulatory approval, testing and cost reductions for broader applications. LS9 has targets in currently existing "drop-in" markets for "FAME" and "fatty acid alcohols" and has developed significant customer relationships for their initial products. Another route is to lock-down offtake agreements with large oil refiners before building scale, to assure demand. Kior, by creating a crude drop-in and a transportation fuel blendstock, may also mitigate these issues since their product should be directly compatible with most crudes, blendstocks, pipelines and refineries. Drop-in chemicals or fuels will be a significant advantage, while Coskata and LanzaTech should be cheaper than existing corn ethanol, displacing an existing product with an environmentally better and cheaper alternative.

To get to volumes, refining/iterating and optimizing technology, understanding markets and the value chain is critical. Smooth "boot-up" is critical. All stakeholder positions must be understood (who benefits and who is harmed by adoption of new fuel) and value must be provided to critical stakeholders for new products to be adopted. For example, an ethanol producer will, to repurpose a plant, require at least similar margins and other de-risking (such as long term off-takes) to switch to a new fuel. Don't count on a "green" premium, other than regulatory benefits like mandates and financial incentives. For this reason, a new technology that gets market acceptance or large off-take agreements up front can significantly de-risk their company's future. On the flip-side, there are many multi-billion dollar markets to provide room for multiple participants. Market size, either in fuels or in specialty chemicals, will not be an issue for any of these technologies. At market competitive replacement costs for drop-in chemistries, the green products will find paths to market over their fossil competitors. Unsubsidized market competitiveness with fossil alternatives, whether through Kior's oil, or the higher value chemicals produced by Amyris, LS9 or Gevo, is the expected outcome over the next few years. For example, the first commercial unit (FCU) for Kior, which will be located in the southeast United States, should hit competitive costs at just 500 tons per day, with low capex. However, if the minimum cost of a cash flow positive facility was $500 million, the financing process for the first unit would take longer, especially without strong, committed partners. A retrofit or bolt-on facility is a good boot-up strategy that companies like Amyris, Gevo, LanzaTech, UOP and LS9 are deploying. Department of Energy or USDA loan guarantees are often the only other bet for debt for companies with high FCU capital cost needs.

Predictability of the "boot-up" is another key consideration. Companies like Synthetic Genomics and Codexis that have laid out 2015 to 2020 timelines to first commercial units should in my view be considered too early to be predictable technology or cost metrics, even with inside information, and I don't currently consider them to be viable biofuels technology providers. And large partners like Shell and Exxon will show conservatism, further slowing down development. My experience indicates that dependence on large corporate partners will sometimes delay technologies by years as they tend to be slow and overly risk averse. In the "far-term" I would prefer radical technologies like Synthetic Genomics.

Capital costs

In general, the capital costs should be less than $5 to 6 per gallon of "ethanol equivalent annual gallon of fuel production" capacity, and that high only if the operating and feedstock costs are about $1 per gallon ethanol equivalent or less (all costs in 2010 dollars) at a minimum. Even then, there is no doubt it is difficult to finance first of a kind commercial units, particularly when the fuel has not yet gained mass acceptance. In the end, $3 per gallon capex on the first few plants, declining over time, would make capital formation easier.

As I mentioned throughout, novel business plans have cropped up as a result, to exploit opportunities or pursue capital light development. For example, LanzaTech, which has targeted both biomass syngas fermentation and waste syngas, has first gone to China to build their backend fermenters onto existing steel mills, obviating the need for investing in a front-end biomass gasifier before proving the technology at scale. Likewise, Gevo decided to retrofit distressed corn ethanol assets to scale up to commercial scale more quickly and less expensively than building from scratch. This is a good example of a smart opportunistic strategy to exploit lower value corn ethanol plants. Amyris and LS9 are taking a similar approach with sugarcane mills, but instead of just retrofitting the entire operation, they are co-investing with the mill owners, bolting their technology onto the existing operating facility and offering higher IRRs to the mill owners as a result. Kior can build a basic, cash flow positive commercial unit for about $100 to 120 million and have 3 to 4 year cash paybacks with well-understood oil industry processes. This has enabled it to finance the first commercial unit, which is now under construction with expected operation in Q1 2012. Coskata has announced USDA loan guarantees to provide the debt for their first commercial unit.

Until detailed commercial engineering starts on a process technology for a “at scale” FCU, capex (and opex) costs may be as much as 100 percent off (sometimes more) – many a naïve estimate of costs is floating around from startups that have never engineered a facility, often ignoring site engineering, wood yard costs, environmental remediation, waste water, transportation facilities etc. To get estimated extrapolations from a demo facility, at least 100,000 gallons a year demo is preferred to even get to 30 percent accuracy on the estimates.

Production Costs:

These are the costs that will make or break many technologies, and are only really known after the process reaches significant scale. They are also the hardest to estimate and face similar uncertainties to those in estimating capital costs and have additional ongoing uncertainty if the feedstock price volatility is high. The major production cost contributions (generally with some exceptions) are feedstock, energy, other process inputs (chemicals, nutrients, catalyst), product extraction, waste treatment, and people. Yield is ultimately a crucial parameter for cost. Yield can be lost in the pathways, or in subsequent purification or processing steps. Regarding energy, every additional step requires more, leading to more cost. In turn, any nasty by-products impact energy, waste remediation costs, and people. The more unit operations required to get from fermentation product to end product, the higher the cost. In the end, if the process hasn’t yet been demonstrated at about 100,000 gallon per year scale, a company’s estimates will be subject to volatility. For fuels, operating costs (ex-feedstock) should be no more than $20 to 25 per barrel of oil equivalent at scale to reach “safer during market volatility” unsubsidized market competitiveness. An ideal target, depending upon process and feedstock should be below $15 per barrel ex-feedstock operating costs in the mid-term. High value chemicals allow for substantially higher costs. Feedstock costs below $60 per barrel (oil equivalent) or roughly $1 per gallon ethanol equivalent are often needed to be competitive and should trend down with scale and time, not up (often a problem with food based feedstocks). Ideal “safe” feedstock costs should ideally be below $40 per barrel ($1 per gallon oil) but definitively below $1 per gallon ethanol equivalent.

Part II: Feedstock.

Feedstock cost, environmental impact and even its politics are critical variables. With each investment one has to pay attention to which feedstocks to get started on, what the process can accommodate over time and the economics, alternative uses and scalability potential (hence the economics to the feedstock producers among their alternatives) for each feedstock.

Technologies that use food-based feedstocks are likely viable in the near term but will have increasing costs, poor politics, and feedstock competition unless the production technique is compatible with cellulosic to sugar hydrolysis technology (such as HCl and others in development).

For fuels, processes that can directly use all components of biomass (cellulose, hemi-cellulose, sugars, starches and lignin) may have an advantage of higher yields per ton and lower costs per ton. Oil based processes for biodiesel are not likely competitive except in niche applications and in certain geographies.

Though multiple cellulose and hemi-cellulose to sugars conversion technologies are in development, personally I am most bullish about some of the recent surprise developments in acid hydrolysis. At scale, HCL-like technologies should be able to produce food and non-food grade sugars at between $0.08 to 0.12 per pound at $50 per ton biomass costs. To speed up and increase cellulosic sugar cost reduction HCL CleanTech has developed a number of front end extraction processes that while contributing to the purity of the sugars, increase the potential of co-product value: their de-acidified lignin is unadulterated (27 percent of the wood dry basis) and tall oils and resins (5 to 7 percent of the wood) are pre-extracted from the wood.

This or similar surprise technology developments could make biomass the new feedstock for sugars based processes. Though traditionalists may argue with me about other technologies that can also convert biomass to sugars cost effectively, such as enzymes and steam or ammonia explosion I have not seen them progress rapidly enough.

In my view "paper mill compatible woodchips", sometimes needed for sugar based processes, will cost in the US at scale $65 to 70 per dry ton, $50 to 60 per dry ton for whole logs for processes that can tolerate bark and wood slash. These prices will start declining quickly in the US as the ecosystem and cultivation of alternative "fuels grade biomass" (which does not need to meet paper mill feedstock quality metrics) develops within five years. The non "paper or lumber" quality biomass ecosystem, which will include co-feed of wood slash, bagasse or corn stover, will develop quickly in the next 5 years as the first commercial cellulosic biofuels units become operational. Mixed biomass feedstock (for technology that can accept agriculture and forest waste mixed with whole logs) will decline towards $40 to $45 per dry ton by 2020 or sooner in the US.

There is a surprising amount of forest waste available; a good example would be hardwood waste, which can reach up to 30% or more of the harvest: southeast timber has roughly 18 to 22 percent waste by mass, whereas the Northeast and Alaska have as much as 30 percent. Ultimately, scaling fuels will depend upon exploiting these near-term available **non-food** feedstocks. In the mid-term (5 to 10 years) winter cover crops (where appropriate) and energy crops planted in crop rotations or on marginal land (over one billion acres of marginal land worldwide has been put out of production due to degradation)[8].

The appropriate perennial, polyculture biomass production approaches, (which can restore degraded lands) will come into play in addition to continued wood, agricultural waste and bagasse use. Long term (10 to 15 years), dramatically improved energy crops, new cropping practices and new chemical fertilizer reduction strategies (such as polycultures) could yield well over a billion tons of biomass in the United States alone, if not substantially more, without significant land impact.

As a result, the most promising technologies must be able to exploit these ligno-cellulosic sources and ideally, mixed feedstocks to have the lowest costs. Use of bark, waste and mixed feedstocks will lower costs and be a significant competitive advantage for any process. Accepting mixed feedstocks will be a major advantage for any conversion process. Such technologies, in my estimation, should yield more than 2000 gallons of fuel per acre (ethanol equivalent) in the long term (versus 400 to 500 gallons per acre today with corn ethanol) to provide material biomass fuels scalability without significant land use impact.

At a high level, at 2000 gallons per acre, to reach 36 billion gallons, we need 18 million acres of land (which need not be farmland), compared to 309 million acres of cropland currently in production (of 406 million acres of total cropland). If one displaces corn ethanol and recovers that land, the numbers for land usage could be substantially lower to meet our 36 billion gallon goal (though corn does co-produce animal feed). In the last 10 years alone, more than 30 million acres went out of production due to degradation, crop yield improvements and conservation.[9] The issue is further complicated by the recovery of land that takes place (covered in more detail in my previous papers) as diets shift from red meat (beef) to white meats (chicken), which take less than 5% of the land beef requires for corn cultivation for animal feed.

In contrast, technologies that focus on specialty oils like jatropha, rape seed (used extensively in Europe for biodiesel), palm oil and the similar are less attractive because their gallon per acre yields are far lower (40-50 gallons per acre for jatropha, up to 600 gallons per acre with palm oil), and we don't expect these oil yields to increase substantially over the next decade. Not only that, jatropha in particular is toxic to animals. Additionally, used restaurant grease, oil from old tires and animal waste, are largely irrelevant as feedstocks at the global scale, though they can be used to produce cost effective fuels where available. As a result, we are not considering them here in detail because in my view, they are not likely to achieve relevant scale, regardless of profitability.

Photosynthetic algae are touted as something exciting due to very high batch yields (suggesting greater than 4000 gallons per acre). However, as discussed earlier, they currently appear to be cost prohibitive for biofuels applications due to high culturing and processing costs, except perhaps for use in specialty products (e.g., Omega 3 supplements, proteins). There are several cost breakthroughs that we believe are necessary for photosynthetic algae to become competitive: *continuous* high strain yields (strain

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[8] Campbell et al., Env. Sci. Technol. (2008)
[9] http://www.ers.usda.gov/statefacts/us.htm

survival and resistance to contamination). That said, there is always the possibility of an unexpected technology disruption of the traditional efforts. The Synthetic Genomics effort, is one such possibility, though unpredictable, long term and with substantial GMO risk, and potentially high reactor costs. Other photosynthetic efforts like Joule are also potential shots on goal. In my view none of the traditional efforts seems currently viable to reach economic costs for fuels and some of the newer approaches are too early to assess predictably. This statement is based on our firm having evaluated dozens of business plans based on photosynthetic algae, though there are ones we have not evaluated.

Meanwhile, there will be numerous opportunities for local, opportunistically low cost local feedstock, but such specific instances can't be relied upon globally and are not generally scalable. Cellulosic sources could be cheaper in other parts of the world. Eucalyptus for example in Brazil can be $30 to 40 per dry ton (used today for steam generation) and bagasse in certain circumstances can cost substantially less. Eucalyptus yields of 6+ tons per acre in drier regions like Matta Grasso and over 9 dry tons per acre (300+ wet tons per hectare in a 7 year growing cycle) in better rain regions like Sao Paulo are common today.

In the mid-term, use of energy canes, new crops and new regions, like the Brazillian Cerrado, could substantially reduce costs as well. Cellulosic and lingo-cellulosic plants are by the far the most scalable feedstock for biofuels on the planet (and most abundant), and will likely be the least expensive as well. Energy crops are likely to play a significant role in the long term and may actually improve row crop agronomy and environmental impact.

Scale

As mentioned earlier, in order to produce biofuels that meaningfully impact global oil demand, yields will have to approach 2000 gallons ethanol equivalent per acre, the feasibility of which I laid out in a previous paper. Achieving this eminently doable target will result in a 75+ percent reduction in land requirements compared to corn ethanol to produce a given quantity of biofuels.

Today, most biofuel demands are met with corn and sugar cane, but it won't remain so for long. Energy crops such as switchgrass and miscanthus will produce 5 to 10 tons of biomass per acre per year in the near term, and will rise to 10 to 15 tons per acre in the decade after the technology for conversion is proven and to 15 to 20 tons per acre or more over the following few decades, if yield improvements similar to those in row crops are achieved. Even sugar cane as a feedstock for fuels may be supplanted by more productive energy crops in a few decades (though sugarcane in Brazil produces an impressive 75 tons of raw material per hectare per year, or 30 wet or 15 dry tons per acre, including sugar, bagasse and leaves). Sugarcane today yields roughly 600 gallons of ethanol per acre today (with no additional energy input).[10] Energy canes that co-produce sugars and biomass or are focused solely on biomass production may increase yields year acre even in the short term (recent data reveals ethanol yields of over 1,200 gallons per acre).[11] This becomes even better with cellulosic sugar conversion technologies.

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[10] http://www.biotechnologyforbiofuels.com/content/1/1/6

[11] http://www.biofuelsdigest.com/blog2/2008/10/22/new-energy-cane-varietals-in-louisiana-have-yields-of-up-to-1240-gallons-per-acre/

Miscanthus has huge potential for rain fed regions, while various grasses like switch grass and sorghum, as well as water efficient plants like agave, are very appropriate for drier regions.

A few years ago, I forecast that as processes mature, one ton of cellulosic biomass will yield 110 gallons of ethanol equivalent, approaching our target of 2000 gallons of ethanol equivalent per acre as yields approach 18 to 20 dry tons per acre. If Kior, for example, is able to reach 2 barrels per ton of production (equivalent to 140 gallon ethanol equivalent per ton) in the next five years, then it will only take 14 tons per acre to reach this 2000 gallon per acre goal; such adjustments to estimates will continue to happen. If these process improvements prove out, we will need smaller yield improvements than I forecast only a few years ago. Encouragingly, Ceres and Mendel, two energy crop companies, forecast biomass crop yields at roughly 15 to 20 tons per acre, depending upon the region, rain and soil.

Again, for comparison, though corn is currently one of the most efficiently grown agricultural products in the world, it only produces 400 to 500 gallons of ethanol from an acre of corn (though animal feed byproducts do increase the effective yield equivalent per acre), with an additional ~300 gallons of ethanol equivalent cellulosic biofuel theoretically possible from the stover. Corn requires prime crop land, which stokes "food versus fuel" politics (perception is important), requires fertilizer, herbicides and pesticides, and is estimated by some sources as not being particularly carbon efficient (various estimates put the savings at 10 to 20 percent compared to gasoline for corn, versus Greater than 50 percent for sugar cane and greater than 70 percent for cellulosic feedstocks), though that is dependent on assumptions. I expect corn-based ethanol will likely be retired as a fuel in the next 10 years as it becomes increasingly uncompetitive.

The sugar or starch based processes that currently run on corn will likely transition to hydrolysed cellulosic sugars, such as the ones produced by HCl Cleantech, which will likely be cheaper, more scalable and less controversial than corn or sugar cane based sugars, probably within the next few years. As for near term cellulosic sources, before other cellulosic sources scale up, we have plentiful supplies of wood chips and wood waste (especially in light of the hundreds of paper mills that have gone out of business in the US in recent years –each site is a potential great biofuels opportunity, with huge benefits to the local communities, which are devastated when paper mills or wood mills shut down) to enable decent scale cellulosic production and to help meet the current 36 billion gallon target for biofuels.

According to the DOE billion ton report from a few years ago, there is roughly 200 million tons of non-merchantable forest material alone. If that is fully utilized, we can approach the 36 billion gallon target at the possible Kior yields with this forest waste alone. Collecting and harnessing even a small amount of this potential waste will create jobs and community income and directly replace billions per year that the US spends on oil imports. And if some people think this is optimistic there are many other sources of biomass like winter cover crops that have not been accounted for.

It's interesting to note that 36 billion gallons, the minimum target under Federal legislation by 2022, is a $90 billion market at $2.50 per gallon of ethanol equivalent. This can support many $10 billion dollar companies in the United States alone. And though I cover only US mandates here, similar mandates exist in Europe and many other countries.

It's also worth pointing out that the US currently consumes just over 280 billion gallons of oil annually,[12] so there's plenty of room for upside, much wealth that can be created, and the phenomenon can be easily replicated in many regions of the world with similar local benefits. Any producer of biofuels that is cost competitive with crude oil will likely find a market, even if it isn't the lowest cost process. Conventional oil supplies, though I expect them generally to be able to scale to meet demand, will come at increasing cost and with increasing environmental, financial and other risks. I am not an ardent believer in peak oil theory though I am not qualified to judge it either.

Agronomic Approaches and Land Use

Biofuels are seen both as an incredible opportunity to improve land quality, biodiversity and the environment, and as a huge threat, depending on who you ask. The devil is in the details; I believe that any biomass effort should be subject to an environmental assessment, similar to my CLAW proposal (Carbon emissions, Land use, Air pollution, and Water use), described briefly in Part I. If managed well, biomass production for energy could usher in a rebirth of the rural economy, through improved and expanding arable land and increased revenue. Dollars that once went overseas will stay in the country and revitalize impoverished communities. The key to making this vision a reality is to explore all options and recognize that one size does not fit all; energy crops, perennials, polycultures, better crop rotations, agroforestry, technological breakthroughs in managing plant nutrition and disease, and new harvesting technology.

For the regressives who project fixed land use and biomass production capacity based on yesterday's technology, un-optimized yields and practices, I just beg to differ. Many people simply refuse to accept that the future can be different from the past and yet extrapolating an unsustainable present is a bankrupt strategy by which to reach a sustainable future. Much research remains to be done but the potential clearly exists for significant jumps in our biomass capacity. With proof of this biomass as a source of liquid fuel, this research will accelerate.

For instance, energy crops like miscanthus have benefits as perennials, and with proper agronomic techniques and technologies can reduce water and nutrient demands while improving soil quality. The cost of biomass is going to be set by marginal land rent and productivity, so good agronomic practices will convert directly into increased revenue (with little environmental impact, or perhaps some benefit) which will ultimately drive down the cost of biomass as its production processes are fine tuned and optimized.

As I have mentioned earlier, while miscanthus has huge potential for rain fed regions, various grasses like switch grass and sorghum may be appropriate for drier regions. Other possibilities include water efficient plants like agave and other plants that use the Crassulacean acid metabolism (CAM) mechanism for drier regions. These "CAM" plants can be five to ten times more water efficient than grasses.

The beauty of cellulosic processes is the flexibility of biomass feedstock, which allows the use of short and long rotations (up to 10 year rotations), agroforestry (interplanted rows of trees and row crops),

[12] Energy Information Administration

and polycultures. Technologies that can use mixed feedstocks will have much lower long-term costs and less price volatility. By using feedstock flexible technologies we have an opportunity to increase biodiversity and symbiotic production of nutrients, which improves soil quality and yields, while not adversely affecting fuel output. Technologies like enzymatic hydrolysis, besides higher early costs, will likely be more feedstock specific and feel less likely to succeed in my opinion.

One option I have previously proposed is the usage of a 10 year x 10 year energy and row crop rotation. As row crops are grown in the usual corn/soy rotation, lands lose topsoil and get degraded, need increased fertilizer and water inputs and decline in biodiversity. By growing no-till, deep rooted perennial energy crops (like miscanthus or switchgrass - see below) for ten years following a ten year row crop (i.e. - corn/soy) cycle, the carbon content of the soil and its biodiversity can be improved and the needs for inputs like fertilizer decreased.

The land can then be returned to row crop cultivation after ten years of no-till energy crops. Currently unusable degraded lands may even be reclaimed for agriculture using these techniques over a few decades. A University of North Dakota study[13] highlights some of the benefits for food crops. We expect similar or even greater benefits for food crop/energy crop long cycle (ten year) rotations, especially in soil carbon content:

(1) Improved yields: a crop grown in rotation with other crops will show significantly higher yields than a crop grown continuously.

(2) Disease control: changing environmental conditions (by changing crops) changes the effect of various diseases that may set in with an individual crop, and crop rotation can limit (and often eliminate) diseases that affect a specific crop.

(3) Carbon content: perennial energy crops in the rotation can increase soil carbon content and reduce the impact of top soil loss materially

(4) Better land: the study notes farmers practicing crop rotations comment on improvements in soil stability and friability. In addition, crop rotations have the potential to increase the efficiency of water usage (by rotation deep-rooted and more moderately-rooted crops or rotation of perennials in long cycles with row crops).

Another potentially important crop practice is the idea of utilizing polyculture species clusters instead of monocultures. This is specifically enabled by the many technology processes which can accept a mixture of biomass types. In the past most human agriculture and forestry required monoculture - one did not want soya beans mixed in with our corn or beans with our grasses! The Land Institute notes that polycultures (and the resulting plant diversity) have significant benefits – from the provision of an "internal supply of nitrogen, management of exotic and other harmful organisms, soil biodiversity, and overall resilience of the system." Further research shows that grasslands that suffer from overgrazing or drought tend to recover faster if there is greater biodiversity.

[13] http://www.ag.ndsu.edu/pubs/plantsci/crops/eb48-1.htm#general

The Australian Rural Industries Research and Development Corporation notes that "Polyculture is shown to offer the proverbial 'free lunch' by producing more from less."[14] The report goes on to note that polycultures yield in greater amounts from smaller areas, and their yields are generally more stable than monocultures (with regards to income level and general risk). Furthermore, polycultures were found to be more efficient in gathering resources such as light, water, and soil nutrients. Other researchers have found similar potential in the yields and environmental benefits of polyculture crops. Though it is hard to extrapolate data from low production potential areas (where these studies were conducted) to the high production potential areas that are needed, we think this is an area that requires further exploration and study.

Meanwhile, winter cover crops like legumes and winter rye (no biomass optimized winter cover crops have been developed, but grasses are a good candidate), grown on row crop lands during their idle period during winters, can yield 3 to 5 tons per acre with no additional land usage and may actually improve land ecology where row crops are grown anyway. In conjunction with winter cover crops, annual crop residue may become a viable supplement to winter cover crops annual biomass yields per acre.

While cover crops have been utilized historically for the agronomic benefits (more on the benefits of crop rotations later), increased biomass yield has not always been a primary area of focus. While many traditional cover crops such as legumes (clovers, vetches, medics, field peas) offer limited potential for biomass yields, other cover crops like small grains (winter rye, wheat, oats, triticale) offer substantial potential – we're confident that they can achieve the 3 to 4.6 ton yields that we project, and perhaps even go further. Currently, these crops (and rye in particular) achieve yields of up to 4 to 5 tons per acre[15]. It is notable that these crops need no irrigation and very little fertilizer.

These crops today are generally managed for forage or grain - managing for forage is perhaps closest to managing for total biomass, but there are still differences in practices that offer potential for substantial yield improvements, along with plant breeding and many of the improved agronomic practices (we discuss these later in the paper). Our research leads us to be optimistic about this area, and we believe further investigation is called for. There are over 300 million acres currently in cultivation, so significant acres could be put into a winter cover crop rotation. At 3 tons per acre, 100 million acres under winter cover crop cultivation would yield nearly 300 million tons of usable biomass per year. And winter cover crops have many environmental benefits including reduced nitrogen run-off.

Perennial polycultures, drought and salt tolerant plants (a huge upside for humanity), long term crop rotations, winter cover crops and innovative low input (water and fertilizer) techniques are very powerful tools in improving agronomy, environmental impact, yields and biodiversity while potentially recovering even non-arable land. Meanwhile, some companies are aiming at dramatically reducing fertilizer and pesticide demand, by developing creative new approaches and technologies. These techniques will shape the ultimate level of impact. In many scenarios, a little imagination, a lot of research and a continued focus on biofuels could actually increase available land by creating incentives to recover degraded lands.

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[14] http://www.rirdc.gov.au/reports/ORG/01-34.pdf

[15] http://www.ag.auburn.edu/aaes/communications/agronomy/ay284smgrfor07.pdf

In my view imagination is in shortest supply when it comes to agronomic econometrics that extrapolate the past to predict the future instead of inventing a new future. I have spoken about this phenomenon elsewhere.

Well over a billion acres of land that was formerly agricultural has been abandoned worldwide because of degradation due to poor farming practices,[16] and there is another billion acres of underutilized grassland, savanna and shrubland that could be used as well.[17] Thinking globally, I suspect that pasture intensification and the land that would free up as the single largest lever that can be pulled to produce biofuels. This is currently managed land, often with very modest return, and there is twice as much of it as there is cropland. At the extreme is the "CREATION" of arable land as was achieved by Embrapa in the Brazilian Cerrado,[18] where tons of lime were deposited to reduce acidity, nitrogen fixing bacteria were employed, and some African grasses and other crops were introduced and specially engineered to thrive in the tropics (soy beans and brachiaria).[19] This gives me much hope.

Biofuel production, if managed well, could result in a vast increase in biodiversity and healthy arable land, with all the benefits to rural economies and quality of life that would bring. More arable land is available in the Brazilian Cerrado today, land that was not arable just a decade ago, with the potential for crop or biomass production, than is under crop cultivation today in India and the US combined. I suspect biofuels and chemicals may be one of the more powerful tools we will have in lifting many rural economies, and much of Africa out of poverty.

Market Dynamics

Every biomass source and crop will have different market dynamics, and it is unclear how the ecosystem will evolve, especially given the expansive options laid out in the previous section. Valuable co-products or synergistic technology pairings are another important part of the economics and may be key to scaling some biofuels cost-effectively (those that cannot use the whole plant). For example, cane and energy crops produce lignin-rich residue with more than enough energy content to power the fuel production facility, creating additional value. Only co-products with markets proportional in size to the liquid fuel market – i.e. commodity animal feed and energy – can realistically be sold to support a biofuels business. One could also co-locate cane sugar-based specialty chemicals production (such as Amyris or LS9), with renewable crude oil production using the underutilized bagasse. Bagasse to oil conversion would create far more value than burning bagasse for electricity, though well-meaning local policies can change that equation completely.

Feedstock price volatility will be mitigated by feedstock flexible technologies, and reinforces the value of using non-food feedstock. As can be seen in the charts below, over similar time periods, corn and sugar have had high volatility (though oil has been worse), while wood products have been stable. The profitability of the corn and sugar-based biofuels companies are very much affected by the price of corn

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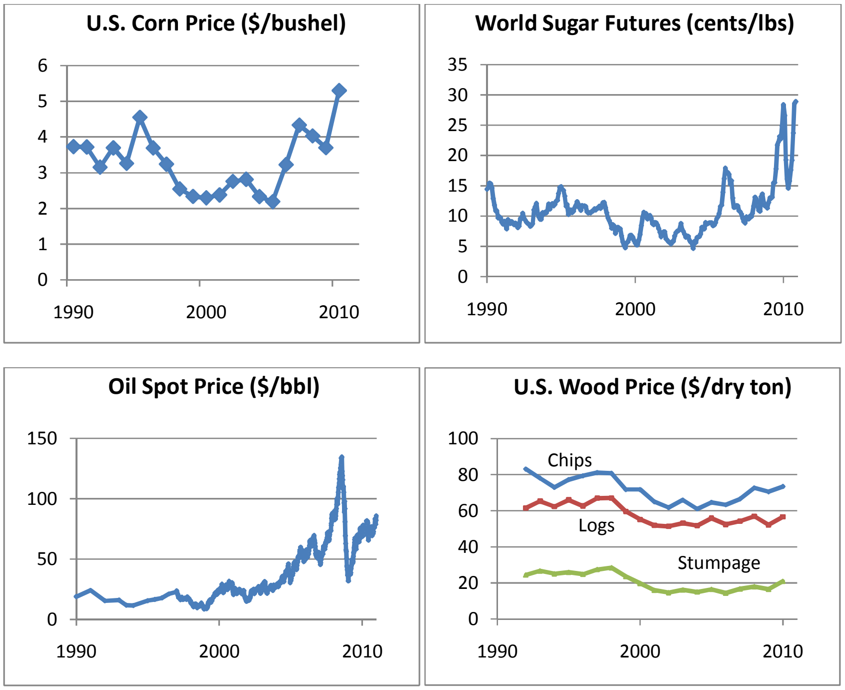
[16] "The Global Potential of Bioenergy on Abandoned Agriculture Lands" J.E. Campbell et al, Stanford University

[17] Land Availability for Biofuel Production; X. Cai et al, Enviro Sci Tech 2011

[18] http://www.economist.com/node/16886442

[19] The Economist; Aug 26th 2010, "The miracle of the cerrado"

and sugar, depending on the value of their co-products. Thus the ability to use biomass such as wood and wood waste, or agricultural waste, is a huge advantage in the uncertain market ahead.



If interest in biofuels sustains and feedstock production becomes a focus, crop varieties and scaled processes will be optimized (e.g., efficient collection and use of agriculture co-feeds and waste, tree bark, saw dust, leaves, energy cane etc), driving down costs in the coming decades. In the short run, collection of sugarcane field waste (often burned in place today), corn stover, corn cobs and other waste could reduce the biomass costs for many processes well below going rates for paper-grade wood chips. When it comes to new plant breeds, the feedstock innovation cycle is likely to be slow, and lag biofuels technology development by 5 to 10 years after the first biofuels plants prove their economics (or oil hits $150- a likely phenomenon). Using corn yield improvements in the past half century as a guide (38 bushels per acre in 1950 to over 160 bushels today), the upside potential in cellulosic feedstock development is substantial.

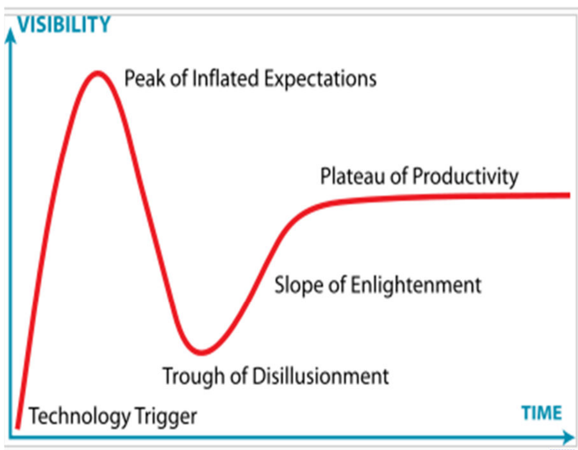
Not only that, biomass to sugars conversion technologies can open up sugar fermentation technologies to the whole world of cellulosic sources by cheaply producing fermentable sugars from cellulosic materials. Sugar and cellulosic feedstock prices will drop as the ecosystem expands and matures. Sugars, as high as $0.20 to $0.30 per pound in the US today (versus 15 to 20 cents per pound internationally),[20] will drop to $0.12 per pound and eventually to $0.08 per pound over the next decade or two from cellulosic sources. These improvements will be driven by crop productivity, sugar conversion technologies, specialized transport and processing equipment, competition and improved logistics efficiency as well as new crops. The flexibility to move from wood to agricultural waste to specialized energy crops and beyond will help stabilize and commoditize the "price per btu" on the open

[20] http://www.indexmundi.com/commodities/?commodity=sugar&months=180

market. If this ecosystem develops, I predict that additional traded markets will appear in the next 10 years for agricultural waste, energy cane, miscanthus, grasses, fermentable hydrolyzed sugars of various grades and "mixed biomass," among many others.

Conclusion

Looking at it from the point of view of the "hype" cycle, we are long past the peak of inflated expectations and have just passed the trough of disillusionment. We are currently on slope of enlightenment on our way to advanced biofuels becoming a significant and positive part of the economy and the energy picture.[21]



Many biofuels technologies have made significant progress over the last few years; there have been some surprises, some partnerships and some clear winners and losers. Some have failed for real technology reasons, but many others for business reasons, market/investor biases or technology-exclusive regulation. Many technologies are as yet unclear and some seem to be promising. There are many positive surprises to come. However, we believe that cellulosic feedstock, regardless of the processing technology and end-product, is the likely winner at scale in the fuels market. Still, sugars will work in the chemicals market.

Over the last few years the industry has seen a tremendous number of strategic and technical iterations coupled with new discoveries. Novel business plans have been developed, to exploit capital light opportunities, as well as to branch out into high value specialty chemicals. It is critical to continue nurturing the next generation biofuel landscape. Though it may appear like a lot of capex is required for many of these projects, there is less market risk and more upside compared to a battery effort like A123 (which has raised roughly $1 billion). The fuels market is huge and established, and all it takes is to be below the market price of this increasingly scarce commodity.

[21] http://en.wikipedia.org/wiki/Hype_cycle

At least half a dozen technologies will be competitive with oil, with some more profitable than others. The critical point is that for the next 10 years at least, there will be an unbounded demand for biofuels, the quantities required by the current mandates both in the US and in many other countries will be an achievable stretch with all the technological innovation. US and worldwide demand of oil will be such that biofuels will not compete with each other, they all compete far more with oil. Each technology is suited to particular local conditions, and with the expected demand, there is lots of room for all these and even more technologies. Within a decade after beginning to scale (2012?), advanced biofuels will become material in the oil supply equation, and will be a significant market force within twenty years. I firmly believe that in 30 years, the price of oil will be more dependent on the marginal cost of land than anything to do with exploration, drilling, OPEC, or Middle East instability.

To those who accuse me of believing because I've invested in these technologies; I continue to invest because I continue to believe.

APPENDIX A:

So what makes a good biofuels investment? Before investing, I evaluate a company on the following checklist. A word of caution; new technologies can change some of these questions or render them irrelevant, and the questions don't apply equally to every technology approach. Consider them guidelines of the kind of questions I ask rather than "mandatory" questions. There are also questions that are missing here that would be appropriate for particular technologies.

I'll be using some math in this section, here are the rough numbers:

Gallon of ethanol equivalent (GEE) = 76,000 BTU per gallon

Gallon of transportation hydrocarbon equivalent (GTHE)[22] = a proxy for "transportation fuels", has the same heating value as a 50 percent gasoline, 50 percent diesel blend – around 122,000 BTU per gallon

Barrel of oil equivalent (BOE) = 42 gallons of crude oil, containing roughly 5.8 million BTU, 48 GTHE, and 76 GEE

1. The first breakeven plant or retrofit for fuels should cost no more than roughly ~$100 million to allow for rapid implementation and easier access to boot-up capital. Boot-up for the first plant is a critical issue and often results in large time delays in projects. Though there are no absolutes here, risk aversion increases exponentially as risk size increases. It also increases exponentially with the size of the organization (think Exxon, Shell, BP) that must take the risk.
2. In part I, I mentioned $5 to $6 capex per GEE for low opex processes, which will pencil out to a good IRR. I also stated that an ideal target would be $3 per gallon of hydrocarbons, or GTHE (which is roughly $1.90 per GEE) for fuels after the first few plants, for the most competitive cellulosic fuels at mid-term maturity. For high value chemicals, targeting $0.25 of gross margin per $1.00 in capex may be a better metric. Capex calculations should be based on true costs, including cost of capital. The most important metric may be a 3 to 5 year payback on the investment which might trump the above metrics as it substantially lowers risk in volatile commodities markets.
3. Feedstocks for fuels should be non-food–based and globally scalable. One off feedstocks reduce a company's ability to scale rapidly. Historical feedstock price stability is very desirable, and processes that accept mixed feedstocks will have a large (availability and cost) competitive advantage.
4. For example, take my hopes for Kior as a likely benchmark for total cash opex. I would expect, with a bit of luck and at $55 per dry ton feedstock costs, to get below cash costs of $1.25 GEE ($ 2.00 GTHE) in a full size 2,500 barrels per day facility by late 2012. By 2015 I expect cash costs to be $0.80 GEE ($1.25 GTHE) with about an equal cost for feedstock and other cash operating costs. This corresponds to a feedstock cost of $0.50 GEE dropping to below $0.40 GEE over time, which is under the target I mentioned in Part I, of $60 BOE (just under $0.80 GEE or $1.25 GTHE) near

[22] Not a generally accepted acronym

term, as well as the “safe” target of $40 BOE (around $0.55 GEE or $0.85 GTHE) by 2015 in a mature facility. Any biofuels company should aspire to beat these metrics.

5. In part I, I mentioned targeting non-feedstock opex of $20 to $25 BOE, (roughly $0.30 to $0.35 GEE) for a mature and competitive technology by 2015, with an ideal target of $15 BOE. Building on that, near term, non-feedstock opex costs should be no more than ~$0.75 GEE (this is $50 BOE, $1.10 GTHE) for fuels in the first few commercial plants, not including feedstock (production costs simply need to be in line with target markets, so pathways targeting high value chemicals can be higher). By 2015, the target should be below $0.40 GEE, though I would like to see numbers below $0.25 per GEE (near $15 per BOE) eventually. This would get us to costs that are profitable at $50 per BOE (for example: $15 per BOE opex, $25 BOE feedstock, plus depreciation and return on capital)
6. For fuels the guideline I use, the cost of the final product cost should be such that feedstock accounts for 50 percent of the total cost, even initially (assuming inexpensive and stable feedstocks). The best will get to where feedstock is 60 to 70 percent of total opex costs (very cheap “other” opex), though technologies like solar fuels (algae) will be exceptions if they can be economic. This comment is generally true of cultivated feedstocks.
7. Feedstocks for specialty chemicals markets can be sugars-based as sufficient scale exists for sugars and starches for the chemicals business but not for a large fuels business.
8. Cost effective boot-up tactics are a critical consideration because a technology that can’t get started in at least one market will never reach its full theoretical potential. Amyris has found some very high value markets. Retrofit/bolt-on approaches like those of Kior, LS9, LanzaTech, Gevo and Amyris are examples of clever boot-up strategy.
9. A demonstration plant or leased capacity should be at least 100,000 gallons per year, and have a clear path to commercial scale. In the end, the only reason for a demo plant is to a) produce samples and b) to verify engineering data. Without this scale a technology cannot be reasonably assessed. Similarly costs for a process that is more than 2 to 3 years to first commercial unit is no better than speculation. Though the appropriate scale can vary and is hotly debated, I use either annual capacity scale or, depending upon the technology, the size of the vessel or fermenter as a guideline to assess the reliability of the costs numbers and scalability of the process. 200 to 300 percent variations from estimates are not abnormal from naïve estimates when technologies are early or technologists inexperienced in large scale projects.
10. The lifecycle carbon emissions should be at least 50 percent less than conventional fuel, even initially, and the technology should have a path to 80 percent carbon reductions. If one gets to 50 percent initially, an 80 percent reduction target as the technology and ecosystem matures is likely.

Table: Representative base, benchmark and ideal targets for cellulosic biofuels production by 2015

Cellulosic Feedstock Estimates	units	2012 Feedstock	2012 Non-feedstock opex	2012 Total cash opex [1]	2015 Feedstock	2015 Non-feedstock opex	2015 Total cash opex [1]	2015 Price per bbl with 15% capex IRR[3]	Comments/assumptions
Base	$/BOE	60.00	35.00	95.00	40.00	20.00	60.00	$ 97.00	$60/ton feedstock [4]
	$/GEE	0.79	0.46	1.25	0.52	0.26	0.79		Capex $3.75 GEE
	$/GTHE	1.26	0.74	2.00	0.84	0.42	1.26		
Likely Benchmark [2]	$/BOE	37.00	43.00	80.00	25.00	20.00	45.00	$ 69.00	$50/ton feedstock [4]
(such as Kior or	$/GEE	0.49	0.56	1.05	0.33	0.26	0.59		$4 capex/GTHE
others)	$/GTHE	0.78	0.90	1.68	0.53	0.42	0.95		yield: 2/ton, 90% availability
Ideal	$/BOE				25.00	15.00	40.00	$ 58.50	$50/ton feedstock [4]
	$/GEE				0.33	0.20	0.52		<$2 capex /GEE
	$/GTHE				0.53	0.32	0.84		yield: 2/ton, 95% availability
Oil Sands	$/BOE						47.00	$ 72.00	25 year asset life
	$/GEE				-	-	0.62		average of multiple players
	$/GTHE				-	-	0.99		rough estimate

Notes:
1 All opex numbers are cash cost only
2 Benchmark is illustrative, best estimates by KV, not representative of any of our companies' strategy or approach
3 Includes 15% IRR, 15 year lifetime, straightline depreciation, 70% debt to equity ratio, 6% debt interest
4 Feedstock prices, depending on location can vary from $10 to $70 per ton
Includes no subsidies or incentives

Energy equivalence	
barrel of oil equivalent (BOE)	1.0
gallon ethanol equivalent (GEE)	76
Gallon of transport hydrocarbon equivalent (50/50 diesel and gasoline) (GTHE)	48

Other questions to ask:

1. **What is their feedstock cost, availability and flexibility?** This in the principle operating cost of most processes. We believe cellulosic sources will be the most scalable in the long-term and most cost effective, for fuels. Broad availability provides relative feedstock cost stability, as primary feedstock production variable costs (like fertilizer or delivery) are linked to and thus hedged by the price by oil.

    a. What feedstocks does the process require now versus possible in the future? Does it use specialty oils or require food-based sugars? If so, is it compatible with hydrolyzed cellulosic sugars like HCL? Can it exploit Waste gases? Does it use Cellulosic materials directly? (We believe the latter two are the best here). Are the prices they project reasonable when scale increases dramatically?

    b. Have they locked up significant feedstock in contracts, or is the feedstock relatively available in the US or globally? Is there anticipated competition for biomass in the locations a company has picked? How replicable is the site?

    c. What has the company proven with current and anticipated feedstocks? Yields, continuous production, costs? At what scale? Have they shown it with industrialized microbes or just lab microbes? Point yields on a small scale, with special conditions, without separation or post-processing can all be used to make claims. Only the 100,000 gallon per year scale demo or larger vessel scale for production verification with industrial feedstocks and microbes should be used to estimate true yields of end products. Most people don't recognize the difficulty in industrializing microbes, waste management, safety issues and start/stop of processes.

    d. Is the feedstock ecosystem on a declining or improving yield and cost trajectory. Trajectory matters critically in all new technologies.

2. **Production cost (ex-feedstock) –** These are the costs that will make or break many technologies, and are only really known after the process reaches significant scale. The key question here is, what has been proven?

    a. Are their production costs compatible with their target markets?

    b. What inputs does their process rely on (e.g., water, chemical additives, nutrients, catalyst, electricity), are those costs predictable and under control?

    c. What are their current yields, how close to theoretical? What are the barriers to getting to ideal yields?

    d. Will they reach their projected costs and be market competitive within 5 to 7 years of their launch (without subsidies)? Ideal prices would be (and I believe can be) market competitive initially.

    e. What product separation/purification or post processing are they using, has it been proven at scale? What purity of inputs is required?

3. **Environmental impact** – using the CLAW framework at least qualitatively but preferably quantitatively. Questions should be asked of the technology as a whole, but also for every deployment/site a company is planning.

    a. How do lifecycle carbon emissions compare to gasoline/diesel?

    b. Does the deployment plan involve minimal or beneficial land use changes? (palm oil has been a huge concern due to clearing of rainforest in some regions). Does the technology or feedstock lead to encroachment of rain forest regions or other virgin land use? I would not take the political and environmental risks personally. Often other political risks exist.

    c. Are there issues associated with airborne emissions during processing or consumption? What has been tested, and at what scale? What are process effluents and local environmental permitting complexity for the technology? Have they been properly accounted for in costs, both capex and opex?

    d. How much water is needed for the process, and how does it compare to gasoline production and refining? Water use should be low, less than 5 gallons of water per gallon of fuel, preferably less than 1 gallon per gallon. Fuel production and refining uses anywhere from 1 to 40[23] gallons of water per gallon of fuel combined, with conventional oil refining claiming around 1 to 2.5 gallons water per gallon of fuel.[24]Water quality requirements if any are also important in these comparisons.

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[23] The higher numbers come from oil extracted using water injection in depleted oil fields

[24] http://www.epa.gov/region9/waterinfrastructure/oilrefineries.html

4. **Scale-up ability –** Quick scaling will decrease adoption risk among competitors, and give a first mover advantage. These questions are directed at the company's end-product

    a. Has the technology been demonstrated at least 100,000 gallons per year scale to have reliable process estimates and cost estimates?

    b. Are the products approved or registered by the appropriate state and federal agencies? More importantly, since many companies are early and immediate registration is not required, I try and assess the risk in getting the products registered.

    c. Is the product fungible with existing infrastructure? Can it be mixed with fuel, oil, other biofuels directly?

    d. Can existing biofuel production assets be leveraged?

    e. How experienced is the team in handling agricultural and petroleum supply chains?

    f. Time to market is critical if a technology hopes to take advantage of mandates and regulatory benefits like tax credits, RINS etc that may disappear within five years. The RFSII regulation in the US has created a huge but time sensitive opportunity. Economics will change over time.

    g. Can a facility be easily replicated exactly ("copy exact") or is each site customized? Is the process designed for remote operation and management so one does not need high level of skills in remote facilities? Customization is often required when a process has waste effluents or needs inputs that are local to a region. Customization increases the difficulty of rapid replication. Need for local skills (versus remote management) makes staffing, training and scaling difficult and more prone to disturbances.

5. **Business plan**: Do they have a clever business plan in place, e.g., through strategic cost-sharing partnerships or distressed assets? Is there creativity in EBITDA sharing models? Has the company demonstrated the ability to collaborate with partners to reduce risk across the enterprise from feedstock supply to product offtake? Risk management is often one of the larger issues in such projects.

6. **Value/Flexibility of end products** – Ethanol is only one possible end-product – some technologies are able to produce a variety of chemicals in order to adjust to changing market demand. Synthetic biology fermentation processes tend to effectively produce a single tailored product, while thermochemical systems create a mixture.

    a. How much product flexibility does the technology offer from the same capex? Can they supply the market at prices competitive with fossil alternatives? A one-off above market price contract (e.g., with government agencies) does not signal scalability of a company or help in making the technology a winning technology globally. We focus on unsubsidized market competitiveness in a company's chosen markets. These markets should be worth at least billions of dollars initially and have potential for expansion.

7. **Financing**: What will be the amount and timing of the financing needed to get to commercial scale and into a self financing mode? What levels of government support (such as DOE or USDA loan guarantees) are included in the financing plan?