Cellulosic Biofuels: Expert Views on Prospects for Advancement

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Abstract

In this paper we structure, obtain and analyze results of an expert elicitation on the relationship between government Research & Development funding and the likelihood of achieving advances in cellulosic biofuel technologies. While there was disagreement among the experts on each of the technologies, the patterns of disagreement suggest several distinct strategies. Selective Thermal Processing appears to be the most promising path, with the main question being how much funding is required to achieve success. Thus, a staged investment in this path is recommended. With respect to gasification, there remains fundamental disagreement over whether success is possible even at higher funding levels. Thus, basic research into the viability of the path makes sense. The Hydrolysis path induced the widest range of responses from the experts, indicating there may be value in collecting more information on this technology.

Keywords: Biofuels; Technology R&D; Uncertainty; Environmental policy

1 Introduction

There has been a great deal of excitement about biofuels recently. The USDOE has funded 3 centers at $125 million each;[1] BP funded a center at $500 million;[2] and it was recently announced that USDOE will spend an additional $786.5 million in research and demonstration projects.[3] Newspapers are full of conflicting accounts of the benefits and hazards of biofuels. In particular, corn-based ethanol has proven to be quite controversial.[4] Thus, the focus of each of the centers above is on cellulosic biofuels (biofuels made from grassy feedstocks, including switchgrass and trees). Additionally, these centers are mainly focussed on a biological path to biofuels – some combination of hydrolysis and fermentation to produce ethanol.

In this paper we consider the role of U.S. government Research and Development (R&D) funding in achieving advances in cellulosic biofuel technology. We have structured and performed expert elicitations to arrive at the relationship between government funding and the likelihood of achieving particular technological targets. We consider a range of technological paths, including hydrolysis/fermentation, but also aqueous phase processing, selective thermal processing, and gasification. These technologies are discussed in more detail in the next section. In Section 3 we describe the development of the elicitation survey, and present the technological endpoints defined by the experts; as well as a cost estimate for each path. In Section 4 we present the results of the elicitations. In Section 5 we perform some analysis, combining expert opinions and deriving efficient R&D portfolios. We conclude with some implications in Section 6.

[1] See http://www.energy.gov/news/5172.htm

[2] http://berkeley.edu/news/media/releases/2007/02/01_ebi.shtml

[3] http://apps1.eere.energy.gov/news/news_detail.cfm/news_id=12490

[4] See for example Searchinger et al [26], and many of the letters in response in Volumes 320-322 of Science. See [24] for an overview of environmental impacts of biofuels.

2 The Technologies

The processes we consider take raw biomass and convert it into liquid fuel. Biomass is composed mostly of carbon, hydrogen, and oxygen in the form of the complex sugar polymers of cellulose and the heterogeneous molecules in lignin. Liquid fuels are also composed of carbon, hydrogen, and to a lesser extent oxygen, in the form of hydrocarbons and alcohols.

But the molecules in biomass take much different forms than those in liquid fuels. Sugars (carbohydrates) combine an equal number of carbon atoms and water molecules. Alcohols contain OH pairs attached to groups consisting of carbon and hydrogen atoms, while hydrocarbons contain only carbon and hydrogen atoms. Carbon molecules can range from very short to very long chains or rings. Larger molecules have more carbon atoms and tend to be more stable and more dense, while burning at higher temperatures. Diesel consists of relatively long carbon chains, while gasoline contains shorter carbon chains.

There are two general steps in converting biomass to commercial fuel. The first step is breaking down biomass from complex and intertwined molecules to an intermediate product consisting of simpler and more separable substances. The second step is to process that intermediate product into a commercial end product with uniform and desirable properties.

Starting with a generic input of cellulosic biomass, such as wood chips, switchgrass, etc. there are several approaches to break down biomass, each of which forms a different intermediate product. For our elicitations, we considered three end-products (gasoline, diesel, and ethanol) and seven distinct technology categories: three related to the first step of primary biomass conversion; and four related to the second step of conversion of intermediate products to liquid biofuels. We did not explicitly cover pre-treatment technologies.

The Selective Thermal Processing (STP) paths involve either pyrolysis or liquefaction followed by refinery methods, and result in a mix of products including both gasoline and diesel. The hydrolysis paths involve hydrolysis to create a sugar solution, and then either Aqueous-Phase processing to produce diesel or fermentation to produce ethanol. The third main direction is gasification, which can produce either diesel or ethanol. Here we describe each technology in more detail.

Selective thermal processing In pyrolysis, biomass is heated to very high temperatures and reactions occur to decompose it without burning. These reactions result in release of gases. Some or all of the gases released are condensed into liquid containing a mix of hydrocarbon chains with properties meeting the specifications given for bio-oil which can then be refined into commercial grade fuel. Liquefaction is similar to pyrolysis but occurs in super-heated water, and produces a different intermediate product, which we refer to as bio-crude.

Acid and enzymatic hydrolysis Decomposition of biomass occurs in a water environment with acid or enzymes added to accelerate the process, breaking down complex polymers into simple sugars in solution.

Gasification By combining oxygen (during partial combustion) and steam (to resulting gases) with carbon compounds, this process converts biomass to Syngas (CO + H2). Syngas can be burned directly, have hydrogen gas extracted, or turned into liquid fuels as considered here.

Refining Refining of bio-oil and bio-crude is much like fossil oil refining. First, the mixture of hydrocarbons is distilled to remove impurities and to separate hydrocarbons into different length chains. Cracking then shortens longer chains to desired lengths. More homogeneous chains or rings are then blended into proportions desirable for gasoline and diesel.

Fermentation Fermentation generally refers to the process of using bacteria to transform carbon molecules. Here, it refers to processes for converting sugars to alcohol, using bacteria in a suitable environment.

Aqueous phase processing Aqueous phase processing (A-P) converts sugars to hydrocarbons. Aqueous phase refers to the water-containing portion of biomass intermediate product. Stable enzymes and catalysts are used to convert simple sugars still in solution into oxygenated hydrocarbons which serve as building blocks for liquid hydrocarbon fuels.

Syngas Conversion Syngas to diesel conversion is based on the Fischer-Tropsch process which uses catalysts to build up hydrocarbon molecules of various lengths from the simple components starting with syngas. Syngas to ethanol conversion occurs through either syngas fermentation or catalytic methods. Syngas fermentation is a specialized type of fermentation using selected techniques and microbes to convert syngas to ethanol. Catalytic methods engineer a series of reactions with chemical catalysts to get the same result.

Multiple Paths to Multiple Endproducts Figure 1 illustrates the feasible paths from biomass feedstock to end product that result from these technologies. The seven technology categories discussed above are represented as squares, with Selective Thermal Processing having two subcategories, pyrolysis and liquefaction. The intermediate and end products are represented as ovals. Each numbered arrow represents a process endpoint that we explicitly assessed. Finally, there are six distinct paths from primary conversion to endproduct, as follows:

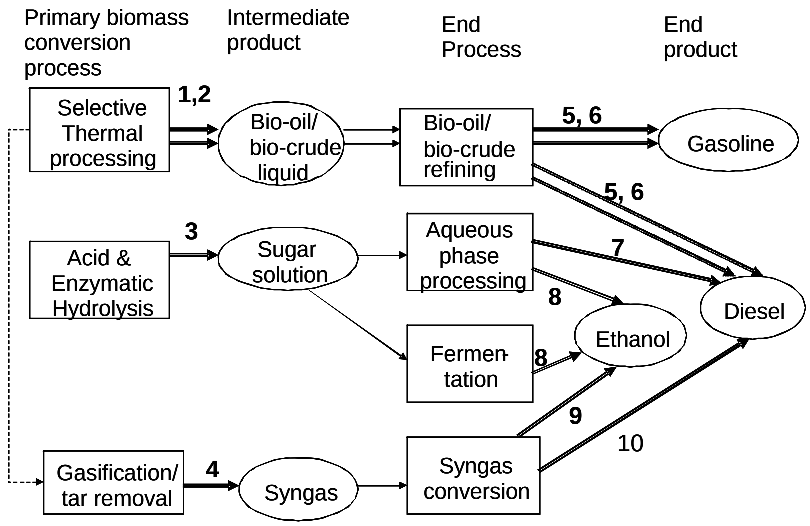

Figure 1: Technological paths from feedstock to end product.

- STP1: pyrolysis followed by bio-oil refining, arrows 1 and 5. Note this results in a combination of gasoline and diesel;
- STP2: liquefaction followed by bio-crude refining, arrows 2 and 6. Again, this results in a combination of gasoline and diesel;
- Hydrolysis1: Hydrolysis followed by traditional A-P, arrows 3 and 7, resulting in diesel;
- Hydrolysis2: Hydrolysis followed by fermentation, or possibly non-traditional A-P, arrows 3 and 8, to produce ethanol;
- Gas1: gasification followed by syngas conversion, arrows 4 and 9, to produce ethanol;
- Gas2: gasification followed by syngas conversion, arrows 4 and 10, to produce diesel.

3 Expert Elicitations

Past data on technological advance contains little information about future technological breakthroughs. In fact, a technological breakthrough, by its nature, is unique; and therefore we cannot use past data and relative frequencies to construct a probability distribution over success for future breakthroughs. Yet, current decisions depend on understanding the likelihood of such breakthroughs. For example, sound government technology R&D policy should consider the *likelihood of success* and the *impacts of success*, along with the total cost of a program, when making decisions [21]. When past data is unavailable or of little use, the alternative is to rely on subjective probability judgements [2]. Expert Elicitations are a formal method for gathering these expert judgements.

Decision analytic methods including expert elicitations [15] have been applied productively to R&D in numerous industries (automotive, pharmaceutical, electronics, etc. See for example [9][27][31]) as well as issues relating to societal decisions [14][19][25]. A recent draft of a USEPA white paper concludes that Expert Elicitation "... should be considered to characterize uncertainty, where it can not be addressed adequately by existing data or additional studies within the necessary timeframe." [13] Most relevantly, a National Research Council study recommends that the U.S. Department of Energy use panel-based probabilistic assessment of R&D programs in making funding decisions [21].

A natural question arises as to how accurate expert elicitations have proven to be in the past. In general, "forecasts" have been problematic, with a prominent example being Herman Kahn and Anthony Wiener's "One Hundred Technical Innovations Very Likely in the Last Third of the Twentieth Century," in which experts attempted to predict 100 "likely" innovations. Albright [1] found that fewer than 50% of the innovations have actually occurred in a widespread manner. This study indicates the weaknesses in informal, deterministic forecasting exercises as opposed to structured probabilistic assessments. For example, the key term representing uncertainty – “very likely” – is never defined, even though the probabilistic meaning associated with the term ranges from 74% to 87% in one study [20]. Moreover, the innovations were not defined unambiguously, so that Albright’s panel of experts had wide disagreement over whether the event had occurred or not. Expert elicitation protocols are intended to explicitly correct for these kinds of errors. Tichy [32] analyzed previous elicitations and found that experts tend to underestimate the difficulties of diffusion, and therefore were consistently over-optimistic, particularly for incremental improvements and organizational innovation. We avoid this bias in our project since we are only assessing the technological breakthrough, and not the likelihood of diffusion through the economy. While diffusion is required to gain benefits, diffusion is related to a number of factors beyond technical feasibility, including the success of competing and complementary technologies, and policy variables related to climate change and energy security. Thus, our assessments are only for technological breakthroughs, not for diffusion. Hultman and Toomey [16] discuss a similar problem of overconfidence, and ask the question are “surprises really that surprising?” They argue that experts have a tendency to be too confident in technologies that have received a great deal of attention. They focus, however, on experts estimating future costs and timelines. In our approach, we may avoid this bias somewhat, in asking explicitly for probabilities for pre-defined cost goals. Additionally, they point out when over-confidence is a problem and when it is not. In particular, if experts are over-confident about bio-fuels across the board, this would have very little effect on a portfolio problem. However, it points out that we may want to be careful in jumping from the data to hard conclusions, as we will discuss further below. All in all, most papers indicate that deterministic forecasts are quite problematic; several biases are common in elicitations and should be corrected to the degree possible; and trying to estimate both technical change and social change increases the difficulty of the activity.

In the rest of this section we describe how we structured assessments and conducted surveys to obtain subjective probability judgments from multiple experts.

3.1 Selection of Experts

We identified a total of seven experts (six individuals and one two-person team), six listed in Table 1 in alphabetical order, and one who preferred not to be listed, from a mix of universities and national labs. Each of our experts has demonstrated expertise in biofuel technologies. The group reflects a range of technical specialties and perspectives; and there are multiple experts capable of providing meaningful assessments of each of the technologies (although not every expert had expertise in all areas).

Richard Bain	National Renewable Energy Lab
Robert Brown	Iowa State University
Bruce Dale	Michigan State University
George Huber	University of Massachusetts, Amherst
Chris Somerville and Harvey Blanch	University of California, Berkeley
Phillip Steele	Mississippi State University

Table 1: Experts

Ideally, we might have used a larger group that represented a wider range of organizations and an international perspective. However, this elicitation is part of a larger project, assessing a number of technologies relevant to climate change over a 2-year time period. Given the large number of technologies that can potentially combat climate change, and the quickly changing nature of these "hot" technologies, a relatively quick and less expensive assessment is appropriate in order to arrive at general insights and inform the setting of priorities for future research in this direction. Here we discuss three issues around our set of experts. First, the number of experts was relatively small. The mean probabilities from small samples are sensitive to the exact set of experts used. Prior work, however, has shown that the incremental value of adding another expert decreases significantly after 3-4 experts [36]. Second, since our interest is on U.S. government spending, we focussed on U.S. experts. We did ask them to consider potential gains that might be made overseas, with or without U.S. funding. We cannot, however, claim to have the full international perspective on the future of biofuels. Third, the experts here represent the academic and laboratory research communities, but not industry. Thus, these experts may be less prepared to estimate the difficulty of actually delivering bio-fuels at the endpoint prices. However, we are primarily interested in scientific breakthroughs that lay the basis for industrial development. Scientific breakthroughs tend to come from research-focussed institutions; incremental improvements tend to come from industry.

3.2 Technological Endpoints

In order to assess probabilities, we need endpoints defined well enough that experts could, after the fact, agree on whether or not they have been achieved [30]. They must make sense to the experts and be useful for policy analysts. There are a number of different approaches to defining endpoints in an elicitation such as this. Because of the number of (possibly interrelated) technologies and performance dimensions under consideration, our approach was to develop one well-defined target endpoint for each technology. This is sufficient to yield probabilities for the ultimate achievement of end product targets with a given set of funding trajectories. It produces a coarse approximation of the efficient frontier and captures the impact on economic value of the interactions between research directions. A more exhaustive approach would be, for each technology, to assess full joint probability distributions over multiple performance dimensions. We believe such an approach may be desirable for finer decisions at a late stage of the funding process once general priorities are clear; however, this would require a very intensive elicitation process that is not justified at this stage of policy analysis.

In Table 2 we present the endpoints that the experts assessed. We derived these endpoints with the input of a subset of the experts listed in Table 1, plus Blaine Metting, Don Stevens and Doug Elliot from PNNL. We chose endpoints that were perceived as challenging by at least a subset of the experts; but were not thought to be impossible by a majority of the experts. While many of the technologies had many different aspects, the two characteristics that we focussed on for all technologies were capital & processing costs and efficiency. The assessed costs *did not* include the cost of feedstock. The costs were specified as potential costs that would be realized given widespread production. Note that all costs reported in this paper are in 2007 dollars. The costs and efficiencies were defined in different ways for the different technologies, according to the preferences of the experts. In addition to these basic characteristics, the experts defined other key characteristics that they believe are crucial for the success of the technology.

One important characteristic was the minimum capacity for the technology. On the one hand, the biological and thermochemical processes tend to have increasing returns to scale. That is, they become more cost efficient on a larger scale. On the other hand, transporting unprocessed feedstock is very expensive, thus this leads to strong incentives for reducing the scale [8]. The third column in Table 2 reports the endpoint for the minimum scale at which the given costs should be viable. Note that without significant technical change research suggests that the efficient size of a plant will be between 5000 - 10,000 tons/day [8], thus the STP path reflects a significant reduction in scale.

Another set of characteristics that were common to many of the technologies were purity standards. Columns five and six of Table 2 reports on these requirements. Each endpoint corresponds to a numbered arrow in Figure 1 above. Some of the costs are in terms of a gallon of gasoline equivalent,

Technology	Cost	Capacity	Efficiency	Other	
1 Pyrolysis	50 ¢/gge (13.2 ¢/L)	200 tons/day (181 tonnes)	50%	Energy density of 19 MJ/Kg	acidity (ph) = 2.5; moisture contest 20%; stability
2 Liquefaction	55 ¢/gge (14.5 ¢/L)			Energy density of 34 MJ/Kg	
3 Hydrolysis	5¢/lb. of sugar (11¢/Kg)		90% (hemicellulose)		
4 Gasification	25 ¢/kg of gas	3000 tons/day (2722 tonnes)		contains less than 1ppm each of tars, sulfur, chlorine, alkali.; 5% nitrogen; 1% methane;	
5 Refine bio-oil	$1/gge ($0.26/L)	200 tons/day (181 tonnes)	40%		
6 Refine bio-crude	$1.5/gge ($0.40/L)		40%		
7 A-P Processing	$1.5/ diesal gal ($0.40/L)		40%, 70%		
8 Fermentation	$1/ethanol gal ($0.26/L)		320 Liters/ton		
9 Syngas to Diesel	$1.5/ gal diesal ($0.40/L)		55% (syngas energy)		
10 Syngas to Ethan	$1/ gal ethanol ($0.26/L)		50%		

Table 2: Technological Endpoints for Elicitation

abbreviated as gge. We have presented the endpoints as defined; we present the metric equivalent in parentheses when the original endpoint was defined in British units. Note that the costs for the end-product processes are inclusive; that is, the total capital and processing cost for diesel is $1.5 per gallon; this includes the cost of producing the sugar solution, bio-oil, or syngas. The efficiency of hydrolysis was only specified for the hemicellulose portion. The experts made their own judgement about the other parts of the feedstock, and incorporated that into their assessment of the total cost of the resulting fuel. We assessed two efficiencies for aqueous-phase processing.

Some experts thought that 70% efficiency was possible, while most thought that was unrealistic. Thus, our results below are for 40% efficiency. For syngas to diesel, efficiency was specified as 55% of the energy in the syngas. For our cost estimates we have made the simplifying assumption that overall efficiency is 55%.

3.2.1 Cost Analysis

In this section we present the results of an example cost analysis (detailed in the supporting materials), in order to compare the different technological paths most directly. The experts were not given this cost analysis when they initially provided probabilities. They were only provided with the endpoints in Table 2. After the elicitation we did circulate the cost analysis, so that experts could confirm this was consistent with their reasoning. The analysis is provided here so that readers can get a sense of how the endpoints add up to a final product.

There are two key parts to the cost analysis. The first is the capital and processing costs. We have specified these in our surveys in terms of a per-gallon cost for the specified end product. In this section we will translate each of these to a cost per gallon of gasoline equivalent. The second part is the feedstock cost. Each technology is associated with an efficiency. This, along with the underlying cost of the feedstock will determine the feedstock portion of the cost. We will assume that the feedstock is switchgrass and the cost is $70/ton ($63.52/tonne) [11].[5] Please note that the actual cost of feedstock will vary, and will be at least partially dependent on the success of biofuels technologies and on the strength of climate change policies. Thus, the costs we present here should not be compared against non-biofuel costs, or against other biofuel estimates using a different assumption about feedstock cost. These estimates are useful for comparing our

[5]This is a central number assuming a yield of 4 tons per acre.

technologies against each other. Table 3 shows the resulting costs per gge C (and equivalent costs per L), and highlights the values of efficiency E, production cost per gallon of endproduct P, and conversion factor v for each of the paths.

Path	fuel	E	P	v	C (per gge)	C (per L)
STP1 (pyrolysis)	gasoline	40%	1	1	2.27	0.60
STP2 (liquefaction)	gasoline	40%	1.5	1	2.77	0.73
Hydrolysis1 (A-P)	diesel	40%	1.5	.88	2.60	0.69
Gas1	ethanol	50%	1	1.52	2.53	0.67
Gas2	diesel	55%	1.5	.88	2.25	0.59
Hydrolysis2	ethanol	$320L/ton$	1	1.52	2.79	0.74

Table 3: Cost per gge

These calculated costs, derived from the endpoints in Table 2, are all in the same neighborhood, and are very close to DOE targets. For example, DOE reports a target cost of ethanol from corn stover as $0.82/gallon of ethanol and efficiency of 90 gal/ton [23]. Using our assumptions this is a gge of $2.43, a bit more optimistic than our endpoint of $2.79. The key difference between the values is in the cost of fermentation. Their target for gasification was again $0.82/gal of ethanol and efficiency of 70 gal/ton [23], giving a total gge of $2.77, a bit less optimistic than ours. The key difference in this case is our very optimistic endpoint for efficiency.

3.3 Elicitation Method

3.3.1 Construction of survey

With the help of a subset of the experts, plus the other advisors mentioned above, we put together a survey. The survey was divided into the 7 technologies and 10 endpoints discussed above. For each technology, we clearly defined the endpoints and stated any assumptions. We then defined two or three funding trajectories. From our early interviews, some experts had suggested that there may be important spillovers between some of the technologies, so our funding trajectories reflect this. (However, the results of the elicitations suggest that the spillovers are not so important). The funding trajectories were set at the beginning and kept for consistency. The funding trajectories are shown in Table 4. Experts were asked to give us probabilities of success conditional on these U.S. government funding trajectories. For endpoints 5 - 10, the experts also conditioned on success in the corresponding primary stage endpoint. For example, in assessing endpoint 5, the experts were told to assume that a bio-oil corresponding to endpoint 1 existed.

Technology	Low Funding	Medium Funding	High Funding
1 Pyrolysis	$2.5M 10 years		$67.5M 10 years
2 Liquefaction	$2.5M 10 years		$67.5M 10 years
3 Hydrolysis	$0 beyond current	$20M 7 years	$270M 10 years
4 Gasification	$5M 10 years	$175M 10 yrs	$175M 10 years + High pyrolisis and Liquefaction
5 Refine bio-oil	$10M 10 years		$100M 10 years
6 Refine bio-crude	$10M 10 years		$100M 10 years
7 A-P Processing	$3M 10 years		$40M 10 years
8 Fermentation	High for A-P only	$10M 10 years	High A-P + $10M 10 years
9 Syngas to Diesel	$2M 10 years		$4M 10 years
10 Syngas to Ethanol	$2M 10 years		$4M 10 years

Table 4: Funding Trajectories

3.3.2 Implementation of Survey

Each expert reviewed a simple primer on subjective probability assessments and filled out the survey. Some surveys were done face to face, some on the telephone, and some were filled out off-line and discussed afterward. We then reviewed their responses with them and asked follow-up questions aimed at reducing the impacts of biases and heuristics. Finally, we sent out a summary of all experts' responses, both numerical and verbal, to be reviewed by all the experts, and allowed

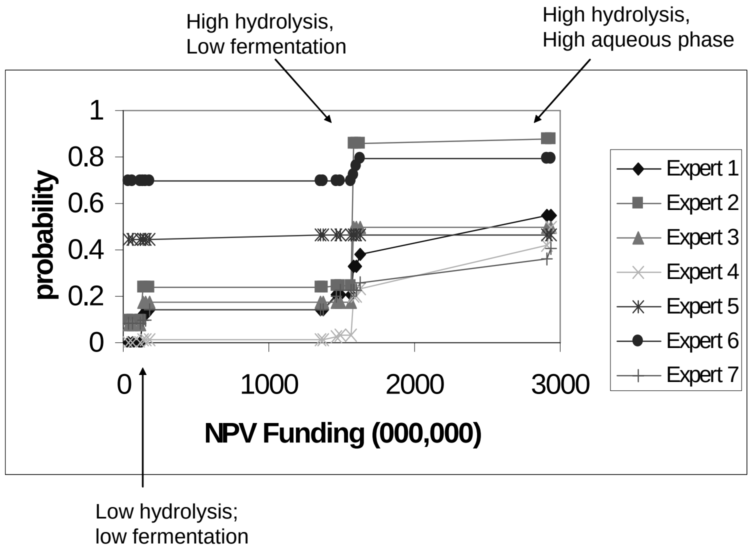

Figure 2: Probabilities of success for the Hydrolysis paths

the experts to amend their answers once more.

4 Elicitation Results

We have summarized the assessments in Tables 1 - 4 in the supporting material. Not every expert answered every question. In particular the experts most associated with the hydrolysis path felt less comfortable answering questions about the thermochemical methods.

Figure 2 shows the elicitation results for the hydrolysis paths (hydrolysis combined with A-P processing and/or fermentation). We see a wide variation in the responses, ranging between 0% and 70% at low funding, and 40% and 88% at high funding. Most experts are consistently on either the optimistic or the pessimistic side. The exception is Expert 2, who believes that the hydrolysis problem is ... “solvable, the issue is that we need more people with more ideas.” Hence, this expert believes that a large amount of funding will greatly increase the probability of success. There was

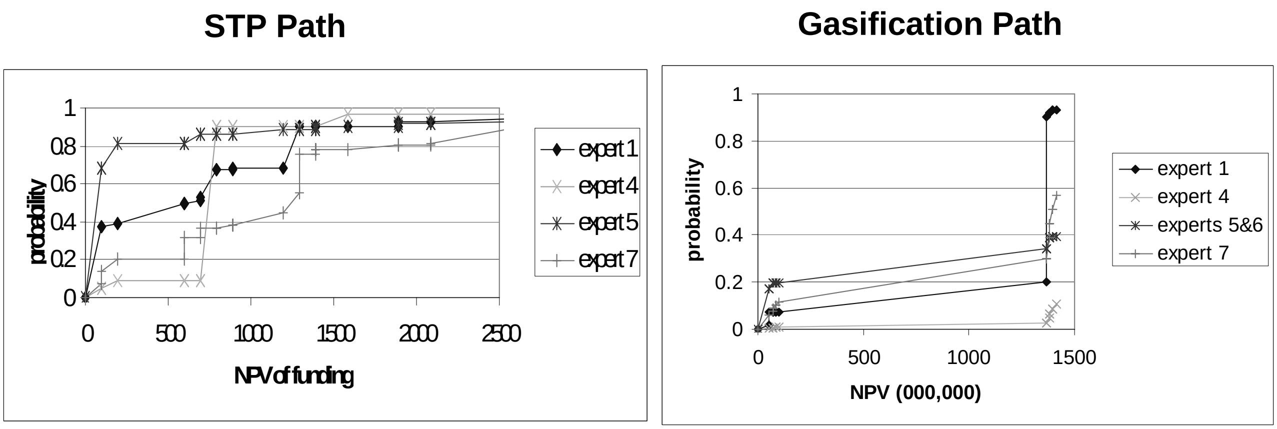

Figure 3: Probabilities of success for the STP and Gasification paths

also disagreement among the experts as to the importance of government funding to industry (as opposed to academia for more basic science) to achieve the stated goals. Expert 1 identified this as a problem of basic research, and Expert 2 specifically said that this problem won't be helped by industry. On the other hand, experts 3, 4, and 6 all specifically mentioned that funding for industry was key.

Finally, three of the experts (2, 3, & 6) in this elicitation are strongly associated with the hydrolysis paths; for the most part they did not answer questions on the other paths. These three experts assigned higher probabilities to the prospects for success given high-funding levels than did the experts with more general backgrounds. Looking at the specific rationales given, we find that the various experts basically agreed about the current state of the art and about the relative ease of achieving the lower targets from there. Both sets of experts also said that the path to the high target was unclear. But while the hydrolysis researchers commented that there were numerous potential solutions from which, with adequate funding, some path to success would likely emerge, the other experts felt that the lack of a clear path meant that the problem could be "recalcitrant".

Exchanges between the experts about these points did not significantly change their judgments. We discuss the interpretation of this phenomenon in more detail in Subsection 4.1.

The left panel in Figure 3 shows the results for the STP paths, including either pyrolysis or liquefaction in the first stage, and refinery techniques for the second stage. Again, we see a great deal of disagreement, but this time only at lower investment levels. Once the investment level gets to about \$1.3 billion, the probabilities converge, and the experts seem to agree that this technology has a good chance of succeeding. In fact, the disagreement in this case seems to be primarily about how much investment is required to give the path a chance of success of around 80%. The most optimistic expert hits this probability at \$200 million, the medium-optimistic expert at \$800 million, and the other two at about \$1.3 billion. This might suggest taking a staged approach to this technology, starting with a commitment to invest \$200 million over 10 years in all four sub-technologies that make up these paths. If success looks imminent, then this phase of investment can conclude; if it becomes apparent that success is quite possible, but more ideas and/or funding for demonstration plants are needed, the funding to refinery methods and/or thermo processing methods can be increased (depending on which path has shown more promise).

The right panel of Figure 3 shows the results for the gasification paths. We have combined the answers of experts 5 & 6, since one answered questions about gasification but not conversion to fuel, and the other answered only about conversion to fuel. For gasification, we see wide disagreement at high funding levels, with the probability of success ranging from 10% to 90%. The most pessimistic expert, however, believes that the probability of success would raise to about 40% if the funding were increased by about \$1 billion. All experts show increasing returns to scale after a large investment in gasification.

4.1 Discussion of Possible Biases

In any expert elicitation, we will be faced with the possibility of conscious and unconscious biases. Performing a formal elicitation with checks helps minimize such biases, but no process can eliminate the possibility altogether. A particular concern in this elicitation is the division between those experts who are associated with the hydrolysis path and the other experts. The experts associated with the hydrolysis path gave it a higher probability of success on average than did the others. There is an argument for giving the judgments of experts closest to the problem the highest weight [10], if they have unique knowledge to contribute. Countering this, there are several potential biases that can come into play: *self-selection* (people who believe in an area of research will focus their work in that area); *optimism* about the likely results of one's own efforts [17]; and the *availability heuristic* where being able to think of examples (e.g., solutions to the problem) leads experts to believe that they are more likely [33]. However, outside experts may underestimate the probability that one of the many solutions could lead to success due to the *catch all bias* [12][7] in which people underestimate the total probability of events that are listed as "something other than the listed possibilities"; or the *disjunctive bias* in which people underestimate the total probability of an entire series of disjunctive events, e.g., in this case, that one of the many possible solutions will work [34]. Finally, it is possible that some of the experts are exhibiting *motivational bias* [29], in which the expert provides probabilities designed to influence a decision. While we cannot rule this out, our interactions with the experts, including reviewing each individual's answers with them in conjunction with all the answers, lead us to believe that this was not a factor. For clarity, we have presented each expert's probabilities separately, and analyzed both the overall mean and the mean of only the hydrolysis experts. For our simple analysis in Section 5 below, evaluating the expected benefit per R&D dollar, this difference had no effect on our conclusions. More in-depth analysis may find different results however.

Returning to Hultman and Koomey [16], our results relate to two of their warnings. First, despite the very high probabilities of success we see on the STP path, it would be wise to keep other technological directions on the table. Second, given that the hydrolysis/fermentation path has been given by far the most attention, both in the press and from funding agencies, we should be especially wary of an optimism bias in this technology.

5 Analysis

5.1 Combining Expert Opinions

For modeling purposes, we can compute returns to R&D for the technologies assuming various combinations of the elicited probabilities. Most simple is to calculate an overall probability of success for each technology path for each expert, based on that expert's expressed probabilities regarding each technology, as shown in Figures 2 and 3 above. This can be used for sensitivity analysis, but gives quite wide ranges. In this section we will focus on the simple average of all experts for illustrative purposes. Given the wide range of expert responses, however, it is best to interpret these averages cautiously [18]. Alternatively, we could get different results from the same data, e.g., by averaging probabilities at the path level rather than the technology level, or giving different weights to different experts [10]. The simple average has the desirable properties of being responsive to all judgments but not prone to large swings based on a single opinion [35].

We have calculated the average probability of success as a function of government R&D for each of the three paths. In Figure 4, we graph the "efficient frontiers" or convex envelopes of these

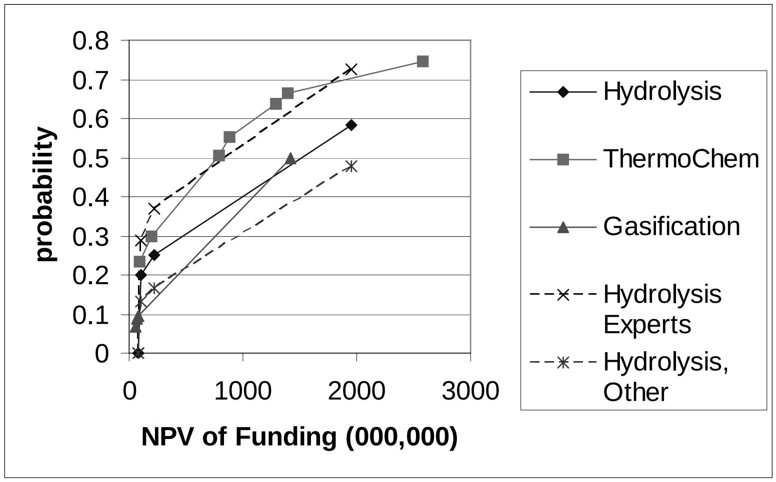

Figure 4: Efficient Frontiers of the Technology Paths

averages. This shows which combinations of projects are most efficient, in the sense of gaining the most probability of success per funding dollar spent. If we use the average of all experts, the STP path looks most promising, ranging from a 30% chance of success at $200 million, to a 75% chance of success at a high funding level of $2.5 billion. However, if we break the Hydrolysis elicitations into two groups we see a different pattern. We have divided the experts into those who are associated with hydrolysis (called "hydrolysis experts" here), and those who are associated with the other methods (called "hydrolysis, other"). When we look at the hydrolysis experts' evaluation of the hydrolysis pathway, it resembles the other experts' valuation of the STP pathway.

5.2 An efficient portfolio

In this section we consider a portfolio funded in order of expected gain per funding dollar invested. Although such heuristics are useful and common in industry, they do not always yield the optimal portfolio. Thus, our results in this section are illustrative. In order to calculate the expected gain, we need an assumption about what the cost of cellulosic biofuels would be with no R&D. We use $3.80/gge for our baseline, "failure" cost. This is based on an estimate in the IEA's report on 1st to 2nd generation biofuels [28]. It is also approximately equal to the cost of a gallon of gasoline assuming a $1000/tonC carbon tax.[6] [7]

For each combination of projects on each path in Table 3, we calculate the probability of success and the Net Present Value (NPV) of the R&D funding trajectory using a discount rate of 5%.[8] We then calculate the expected gain per funding dollar, by calculating the expected cost of biofuels for a given path, subtracting that from $3.80 to get the gain, and then dividing that by the NPV of funding. For each technology category, we lined projects up in order of expected gain per dollar of funding, and eliminated any that were not efficient. Finally, we combined all three categories, and again eliminated those projects that were not efficient. This resulted in one potential funding order for biofuels R&D, illustrated in Figure 5. This funding order did not change even if we used only the hydrolysis experts' probabilities for the hydrolysis path.

All but two of the projects in this portfolio are part of the STP path. This is because these projects have high probabilities of success and low-cost endpoints. The only non-STP points on the efficient frontier is a low investment in A-P processing combined with medium investments in hydrolysis and fermentation; and finally a high investment in all three of these technologies as the final point on the curve. None of the gasification projects are on the efficient frontier.

The left panel of Figure 5 shows the expected cost of biofuels as a function of R&D spending.

[6] This assumes a cost of gasoline of 90 cents/gal wholesale (http://www.oregon.gov/ENERGY/RENEW/Biomass/Cost.shtml); and 19 lbs of CO_2 per gallon.

[7] The choice of "failure" cost does not have a significant impact in this case. We considered a failure cost of $5/gge, and came up with essentially the same portfolio. A much lower failure cost, of say $2.80/gge would eliminate any interest in the higher cost paths such as fermentation and liquefaction.

[8] The specific choice of discount rate has very little effect on the relative expected gain per funding dollar. A low discount rate is appropriate for government funding. NOAA, for example, suggests 3% [22]

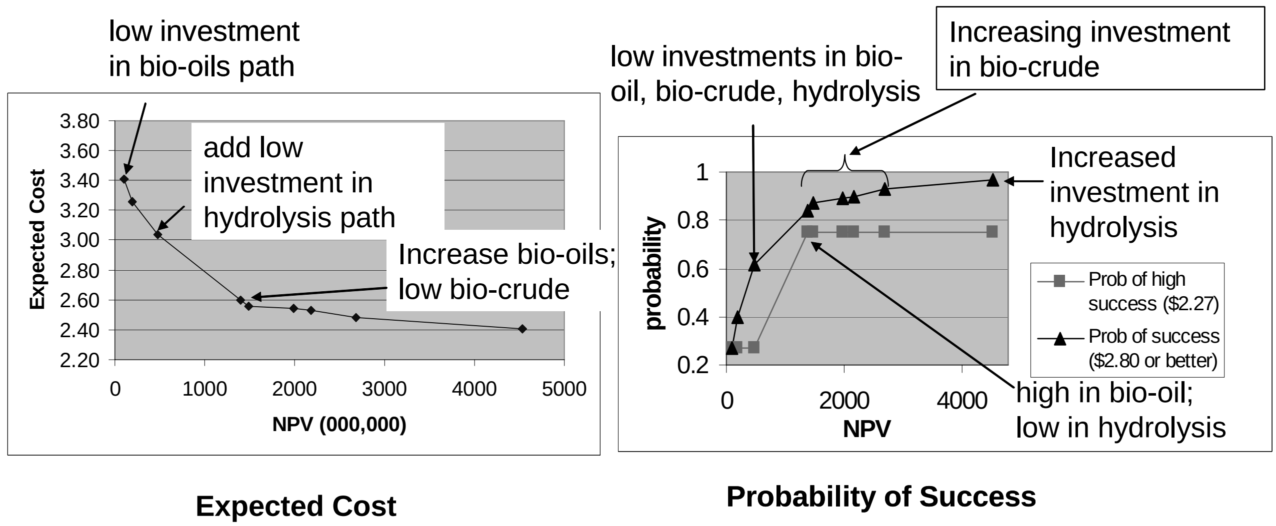

Figure 5: The expected cost and probability of success of the efficient portfolio as a function of R&D investment.

We have highlighted key investments. The first, most efficient investment is into the bio-oils part of the STP path – pyrolysis combined with bio-oils refining. This is followed by an investment into the bio-crude path, and then investment into the hydrolysis path, including hydrolysis, aqueous phase processing and fermentation. All the other investments are on the STP path, with the bio-oils path more efficient than the bio-crude path. The final point includes high investments in both the STP paths and in the hydrolysis path.

The right panel of Figure 5 shows the results in a way that highlights the probabilistic nature, showing how the probabilities of success are related to US R&D spending. We have broken it into two categories. The highest line shows the probability of any success, that is, the probability that the cost/gge will be $2.80 or less; the lowest line shows the probability that the most ambitious target will be met with a cost of $2.27.

6 Discussion

One way to address climate change, fossil resource depletion, and other environmental problems in the transportation sector is through the development of cost-effective cellulosic bio-fuels. In this paper we have presented the results of an expert elicitation on the potential to reduce the cost of cellulosic biofuels through government funded R&D.

We found a wide variety of opinions among the seven experts. The different technological paths, however, had different patterns of disagreement. On the selective thermal processing path we saw that the experts differed primarily on the amount of funding that would be needed to achieve a high probability of success. All experts agreed that the probability of success is at least 80% if the funding is high enough. This implies that a strategy of staged investment in this path makes the most sense.

On the hydrolysis path, the difference of opinion was more severe. Two experts were relatively optimistic, but saw little impact of funding – that is, they believe the endpoints are likely to be achieved with or without significant government funding. One expert had the direct opposite opinion, that the problem is certainly solvable, but will require significant government funding. The remaining experts follow a smoothly increasing path, with the probability of success increasing with government funding. However, on average, this group only gives the technology about a 40% chance of success. This suggests an approach to first wait and see what the results of the current funding are; if this proves promising, but requires more investment, then invest in hydrolysis; again if this is promising but the final product is not forthcoming, invest in a combination of Aqueous-Phase processing and fermentation. Moreover, the large difference of opinion in this case suggests that it may be valuable to perform more in-depth elicitations on this topic, aimed at clearly defining any technological disagreements, and testing for and correcting specific biases.

The gasification path had yet a different pattern. Here, we see agreement that at low funding levels the chance of success is very low, and that there are increasing returns to scale with larger investments. However, there appears to be a fundamental disagreement over how viable the technological endpoints as defined are. This suggests starting with investment in knowledge-gathering and risk-reduction rather than in the development of the technology itself. That is, the best way forward would be to run experiments needed to ascertain whether these endpoints are feasible. Only if the community feels the likelihood of success is great enough would we then proceed with the large investments needed to achieve success.

Using the average of the experts, we found that the STP path generally had the highest expected benefits per funding dollar. This is because the bio-oils path, in particular, had the most favorable endpoint *and* the highest probabilities of success. However, a moderate investment in the hydrolysis path (consisting of \$20M, \$10M, and \$3M per year in hydrolysis, fermentation, and aqueous-phase processing) was also very efficient.

This elicitation was part of a larger project, covering seven technological categories (solar [4], CCS [5], nuclear [3], batteries [6], bio-electricity, and grid integration) over a two-year period. Thus, each individual elicitation was relatively quick and inexpensive. Given the large number of potential technologies to combat climate change, and the speed of technological change in these hot areas, quick and inexpensive elicitations have value in pointing to general trends, providing estimates of the value of information, and underlining questions that would need to be addressed in more detailed elicitations. We have reported the results of the elicitations, but we have (as we believe is appropriate) interpreted them with some caution. A more extensive study could engage a larger and more diverse group of experts, and survey additional technological endpoints.

This work is intended to inform the debate on research directions by providing a snap shot of what experts in the field see as possibilities right now, and outlining trends that may be interesting for making funding decisions. We stress that the disagreements between experts can be as informative as the agreements; and therefore the simple average over experts, while one useful metric of analysis, are not be the only finding of this paper. In fact, the disagreements have shown the way to several research steps that could be aimed at gathering information in order to improve the value created by future research expenditures.

Cellulosic biofuel technology is probably needed for bio-fuels to succeed in the long run. A back-of-the-envelope calculation, assuming a goal of using biofuels for 20% of transportation liquid fuels in 2020, indicates that a savings of $1/gge in the cost of biofuels would translate to a savings of $20 billion/year.[9] The actual value to society will depend on a number of factors, including the impact of landuse, the severity of climate change, and the costs of competing technologies, particularly electric vehicles.

Understanding exactly which paths and projects should be pursued, at what levels and in which order, would require a comprehensive portfolio analysis. In this initial step, we divided biofuels efforts in terms of processes, intermediate products and end-products, and defined funding assumptions and target endpoints. These facilitated expert elicitations that translate into economic cases for the members of this inter-related family of technology investments.

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[9] The EIA forecasts the demand for liquid fuels in transportation will be about 14.65 million barrels of oil a day in 2020, or 287 million gallons of gasoline. If biofuels make up 20% of this, then that would be about 57 million gge/day, or over 20 billion gge per year.

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