1-1-2011

Cellulosic biofuels: Expert views on prospects for advancement

Erin D. Baker

Jeffrey M. Keisler
University of Massachusetts Boston, jeff.keisler@umb.edu

Cellulosic Biofuels: Expert Views on Prospects for Advancement

Erin Baker, Jeffrey M. Keisler

University of Massachusetts, Amherst

University of Massachusetts, Boston

Abstract

In this paper we structure, obtain and analyze results of an expert elicitation on the relationship between U. S. 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 looks promising. 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:

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

[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 [1], and many of the letters in response in Volumes 320-322 of Science. See [2] for an overview of environmental impacts of biofuels.

mainly focused 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 estimate 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. We focus on technological breakthroughs that will, if achieved, lead to large, discontinuous reductions in the cost of producing biofuels from cellulosic feedstock. This is in contrast to the incremental cost reductions related to learning by doing [3].

In the next section we discuss the advantages and challenges of expert elicitations as a method for supporting R&D funding decisions; and preview the rest of the paper.

2. 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, a National Academy studied concluded that 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 [4]. When past data is unavailable or of little use on its own, the alternative is to rely on subjective probability judgements [5].[5] Expert Elicitations are a formal method for gathering these expert judgements.

Decision analytic methods including expert elicitations [7] have been applied productively to R&D in numerous industries (automotive, pharmaceutical, electronics, etc. See for example [8][9][10]), to issues relating to societal decisions [11][12][13], as well as to energy planning and policy analysis ([14], see [15]). Notably, 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 [4].

This paper is part of the first step in a larger project intended to inform climate change energy technology R&D portfolios. As part of this project we have performed expert elicitations on solar photovoltaics [16], carbon capture and storage [17], nuclear fission [18], batteries for vehicles [19], and electricity from biomass. The second step of the project is to determine the impact of technical change, if it is successful, on the cost of reducing greenhouse gas emissions. The

[5] It is sometime possible to combine such judgments with historical data [6].

third step is to combine the elicited probabilities and the impacts on abatement costs in an R&D portfolio model to get insights about the optimal level of R&D spending and the composition of the portfolio.

The expert elicitations provide a starting point for the analysis. We can use our initial sets of elicitations in combination with an R&D portfolio model to calculate the value of more information. We will likely find that there is a high value of information on some of the technologies, but a low value on some of the other technologies. Specifically, information has high value if (1) it has substantial probability of changing the optimal choice and (2) in cases where this change occurs it has a large effect on the overall value.

It is hard to judge *a priori* which information will have the most value. In light of this, and because there are many interesting energy technologies in the climate change arena, our initial sets of experts are somewhat small, in this case a range of 4-7 experts on the individual technologies. This allows us to pilot our elicitation methods, to get thorough qualitative information through our interviews, and provides baseline data for prioritizing future elicitations. Moreover, prior work has shown that the incremental value of adding another expert decreases significantly after 3-4 experts, primarily due to natural correlations among experts [20]. Thus, the results presented in this paper should be taken as a starting point for future work – and future conversations – on the potential for biofuels technology

The biofuels technology area provided special challenges as we structured our elicitations. A key contribution of this paper is to lay out a methodology for structuring elicitations when a field consists of a portfolio of overlapping technologies. Specifically, as discussed in detail in the next section, we divided the process of turning biomass into liquid fuel into two parts, primary conversion of biomass into intermediate products and end processes to produce a set of end products. This innovation allows us to analyze a portfolio of discrete R&D efforts that result in improvements to an overall production system in a way that is amenable both to obtaining expert judgments and calculating the impact on the system of successful work in each area.

In the next section we provide a brief overview of the technologies that we considered; and introduce our structure, combining technologies into paths leading to endproducts. In Section 4 we present the methods we used to perform the elicitations. We discuss the selection of experts; and describe the specific endpoints that were defined in order to elicit probabilities. We provide an example of a cost analysis to give a sense of how the technological endpoints relate to cost at the pump. The cost analysis is an example, however, not a prediction of future costs, because the cost of the biomass feedstock is a key driver of the overall cost of biofuel. The cost of the biomass feedstock depends on a number of economic variables and thus is not a purely technological variable. In Section 5 we present the results of the elicitation, including the full range of probabilities elicited and many of the qualitative comments provided by the experts, as well as a discussion of possible biases. This is the core of the paper. In Section 6 we do some initial analysis, showing the effects of combining the expert opinions. We conclude with some implications in Section 7.

3. The Technologies

The processes we consider take raw biomass and convert it into liquid fuel. 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. To limit the scope of the project, 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.

In **pyrolysis**, biomass is heated so that thermal decomposition reactions occur, releasing vapors. Some of these vapors can be condensed into a liquid product we will call bio-oil. **Liquefaction** is the thermal decomposition of solid biomass in a solvent which is usually water. Liquefaction also produces a similar liquid product, which we will call bio-crude to differentiate it from the bio-oil produced by pyrolysis. **Hydrolysis** refers to the decomposition of biomass in a water environment with acid or enzymes added to accelerate the process, breaking down complex polymers into simple sugars in solution. **Gasification** combines oxygen (during partial combustion) and steam (to resulting gases) with carbon compounds, converting biomass to Syngas (CO + H2). Syngas can be burned directly, have hydrogen gas extracted, or turned into liquid fuels as considered here. **Refining** of bio-oil and bio-crude is much like fossil oil refining. **Fermentation** refers to processes for converting sugars to alcohol, using bacteria in a suitable environment. **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 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 sub-categories, 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:

- 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.

4. Methodology

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

4.1. 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).

Ideally, we might have used a larger group that represented a wider range of organizations and an international perspective. However, as mentioned above, this elicitation is part of a larger project, assessing a number of technologies relevant to climate change. 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 [20]. Second, since our interest is on U.S. government spending, we focused on U.S. experts. While our experts did consider potential gains that might be made overseas, with or without U.S. funding, the focus of this study is in the U.S, and therefore we cannot claim to have an 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-focused institutions; incremental improvements tend to come from industry.

4.2. 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 [21][22][23]. 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 defined these endpoints iteratively over a number of individual conversations with a subset of the experts described in Table 1, plus three additional experts from PNNL (who did not participate in the full survey due to scheduling constraints). 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. Please note that the information in Table 2 should not be interpreted as *data* in terms of representing characteristics of current technologies. Rather, the endpoints represent a description of a possible future technology. The idea is to then determine the likelihood of actually achieving these endpoints.

While many of the technologies had numerous interesting characteristics, the two characteristics that we focused 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. For example, the experts were most comfortable assessing the efficiency of thermochemical methods in terms of percent efficiency, but for fermentation, in terms of liters of ethanol per ton of biomass. Thus, in Table 2 we present the endpoints as the experts assessed them, and provide conversions into international units when needed. In Section 4.2.1 below we discuss how these varied parameters can be converted to common metrics.

In addition to these basic characteristics, the experts defined other key characteristics 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. On the other hand, transporting unprocessed feedstock is very expensive, thus this leads to strong incentives for reducing the scale [24]. 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 [24], 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, 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%.

4.2.1. 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 determines the feedstock portion of the cost. We assume that the feedstock is switchgrass and the cost is \$70/ton (\$63.52/tonne) [25].[6] 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 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. The cost per gge is found by using the following equation:

$$C = \frac{f}{E} + Pv \tag{1}$$

where f is the cost per gge of the feedstock.[7] Figure 2 shows how sensitive the calculated costs are to assumptions about the cost of the biomass feedstock.

These calculated costs, derived from the endpoints in Table 2, are all in the same neighborhood, and are consistent with the conclusion in [26] that "2nd generation biofuels costs will not be "significantly below today's production cost level of the 1st generation biofuels."

Additionally, our numbers 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 [27]. 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 [27], 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.

4.3. Construction of survey

With the help of the experts and advisors as mentioned above, we created 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

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

[7] $f = \frac{c_f \text{ \$/ton}}{15{,}900{,}000 \text{ btu/ton}} * 115000$ btu/gge where $c_f = 70$ for our baseline case.

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.

4.4. Implementation of Survey

Each expert reviewed a simple primer on subjective probability assessments and filled out the survey. Some surveys were completed 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 [28] e.g., querying about whether they had considered disconfirming evidence for their view – especially where other experts held different views; asking backcasting type questions; and reminding the experts about overconfidence and prospect theory type biases for probabilities close to 0% and 100%. Finally, we sent out a summary of all experts' responses, both numerical and verbal, to be reviewed by all the experts, and allowed the experts to amend their answers once more.

5. Elicitation Results

5.1. Detailed Results

In this section we provide the detailed results of the elicitations in Tables 5 - 9. We provide a summary of the responses and rationales we received from the experts below each table. 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.

Consider the Hydrolysis columns in Table 5. Regarding the low funding trajectory Expert 1 said "The very significant $450 million federal investment in the GTL Bioenergy Centers is distributed over five years. Given that the focus of this work is very basic science, it is unlikely that the defined endpoint will be reached in the five years of current program funding. The addition of $20 million/yr for combined basic and applied research provides relatively little toward the considerable engineering R&D are required to meet the enormous challenge of depolymerizing cellulose to sugars." This general view was shared by most of the experts, with the exception of expert 6. This expert felt that the endpoint as defined, only specifying the hemi-cellulosic portion, was relatively easy to achieve without any additional funding. Regarding the impact of high funding, again expert 1 provides a clear analysis: "Developing systems of enzymes to depolymerize biomass is a challenge far greater than anything tackled by the biotechnology research community in the past. As described by the GTL Bioenergy Roadmap released two years ago by the U.S. DOE, substantive progress will require a deep understanding of enzyme kinetics and microbial metabolic pathways. It is hard to rush basic research – it could take 20 years to unravel enzymatic hydrolysis sufficiently to produce inexpensive fermentation substrate." Expert 2, on the other hand, felt that the timeframe was not the crucial factor – he saw no need for high funding over a very long period – but rather stressed that the importance of an infusion of funding is to attract more high quality researchers. Experts 3 and 7 both comment that they are concerned about achieving a cost of 5 cents per pound.

Considering tables 5 and 6, we see that the experts were generally more optimistic about pyrolysis than liquefaction, and generally had very high probabilities of success. Most commented that the pyrolysis endpoint is very close to what is being seen today, with two exceptions: stability of the bio-oil, and the low processing cost. All experts agreed that the high funding trajectory had a very good chance of success, with the caveat that this assumed the research effort was highly coordinated and efficient.

The experts noted that the low funding trajectory for liquefaction is similar to the funding level for the past 10 years, in which little progress has been seen. Expert 6 notes that achieving the energy density will require taking out oxygen and de-watering in a cost effective way; and that this will be a particular challenge at the small scale of 200 tons per day.

Regarding gasification, the experts disagreed about the stringency of the target, with Expert 1 arguing that the endpoint as defined can be achieved if we allow for a very large scale. The real challenge, he argues, is to achieve a similar endpoint at a smaller scale. He gives a low probability since he feels the work to achieve the endpoint is more on the development side and requires much larger funding. The other experts noted that a great deal of money has been spent on this technology for many years and progress has been very slow; therefore a small amount of money into basic research seems unlikely to result in a breakthrough. Most agreed that the high funding trajectory, in supporting development as well as basic research, was promising. Expert 7 believes that there is a real likelihood of spillovers from pyrolysis research, arguing that there is opportunity for thermal processing at pyrolysis temperatures to add to the success of the effort for tar removal during gasification, as much of the processing and analytical equipment is the same; the catalytic route to tar removal may easily be assisted by the trend toward catalytic pyrolysis research.

Regarding A-P (in Table 7), Experts 6 and 7 agree that the low funding level is too little to allow several independent researchers to develop the infrastructure required to allow significant probability of success. Expert 1 argues that "Basic research is likely to yield significant advances in the understanding how sugars can be catalytically upgraded to fuels and commodity chemicals," but that the low funding level is not likely to lead to "commercially viable transportation fuel." Expert 2 discusses the need to find a long-life catalyst at a reasonable cost.

The table shows the most common result for fermentation is a relatively high chance of success at the low funding level, and little improvement with increased funding. The main rationale is that the large, currently funded centers are likely to achieve this endpoint on their own. Even experts 4 and 7, who see some improvement with higher funding, feel this improvement is modest.

Regarding bio-oil refining (see Table 8), Expert 1 suggests that "The very limited data available suggests that this is a very promising approach to biofuels," however, the limited data also implies it is quite uncertain. Expert 7 comments that this is a very low amount of funding for refinery-scale research; and is concerned that the stated cost goal is quite low. All experts agree that success is likely at the high funding levels. The experts note that the bio-crude technology is similar to bio-oil, with a key difference being that while it is more expensive to make bio-crude from liquefaction, it is less expensive to turn it into end products.

Experts 1 and 5 commented that the syngas-to-endproduct processes (in Table 9) are essentially industrial processes that already exist – the low level of funding is unlikely to make much difference. One key remaining hurdle is to either demonstrate that contaminants can be removed at levels that will prevent poisoning of syngas catalysts; or to develop new catalysts that are resistant to contaminants. Experts 4 and 7 see the key challenge in achieving efficiency of 55%.

5.1.1. Qualitative summary of detailed results

In the data above, we see many cases of a significant jump in probabilities with an increase in funding. However, the rationales for these increases seem to be divided into two categories. The first category includes technologies in which the experts see the challenge as primarily a scientific breakthrough. In this case, the argument for higher funding is to increase the scope of the research, mainly through an increased number of researchers, perhaps by extending the research period. This implies a vision of R&D as a search: there are many possible avenues, the more we search sooner, the higher the likelihood of finding the right one. The technologies in this category are hydrolysis and STP in primary conversion and A-P and STP in end-product processing.

The second category includes technologies in which experts see the main challenge being amenable to engineering or development (the D in R&D). For these technologies, the experts seem less optimistic about achieving a scientific breakthrough, but imply that great strides may be reached through a concerted effort in development. Development is by its nature a high-resource activity; and is made more so when the technologies themselves are at large scale. The technologies in this category are primarily those on the gasification path, but some experts indicated that refining and A-P have some similar challenges.

Finally, we see that experts pay attention to how much past funding a technology has received (or is receiving). In the case of fermentation, five out of seven experts imply that the current level of funding is sufficient, additional funding is unlikely to show much effect. This affected gasification as well, as experts noted the amount of research that has already gone into this technology, and therefore doubted that incremental funding would have any impact at all. This seems to have influenced the elicited probabilities for liquefaction as well, with experts noting that recent efforts have not resulted in breakthroughs. On the other hand, pyrolysis seemed to get the benefit of the doubt from experts, since it has received so little funding in the past.

5.2. Combined Results for each Path

In this section we combine the results for each individual technology to show the overall impact of funding on the probability of success of the three key paths – Hydrolysis, STP, and Gas.

Figure 3 shows the results for the hydrolysis paths (hydrolysis combined with A-P processing and/or fermentation). We see a wide variation in the combined probabilities, 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 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 5.3.

Figures 4 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 thermal processing methods can be increased (depending on which path has shown more promise).

Figure 5 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.

5.3. 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 [29], 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 [30]; 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 [31]. However, outside experts may underestimate the probability that one of the many solutions could lead to success due to the *catch all bias* [32][33] 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* [23], 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 6 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.

Hultman and Toomey [35] discuss 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. Our approach avoids this bias to some extent, 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. 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.

Tichy [36] 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.

6. Analysis

6.1. 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 3 and **??** 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 [37]. 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 [29]. The simple average has the desirable properties of being responsive to all judgments but not prone to large swings based on a single opinion [38].

We have calculated the average probability of success as a function of government R&D for each of the three paths. In Figure 6 we graph the "efficient frontiers" or convex envelopes of these 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.

6.2. 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. Noting this fact, and the preliminary nature of our results, the curves shown here should be considered as 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 [39]. It is also approximately equal to the cost of a gallon of gasoline assuming a $1000/tonC carbon tax.[8] [9]

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%.[10] We then calculate the expected gain per funding dollar: $\frac{3.80-E[C]}{NPV}$. 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 6. 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;

[8] 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.

[9] 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.

[10] 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% [40]

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.

Figure 7 shows the expected cost of biofuels as a function of R&D spending. 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.

Figure 8 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.

7. 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; particularly since the path is divided into a number of technology programs that can realistically be invested in one at a time.

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. The comments provided by the experts suggested that this technology was the least likely to experience a technological breakthrough, but that it may benefit from concerted development efforts.

When we averaged the experts, we found that the STP path generally had the highest expected benefits per funding dollar because the bio-oils path had the most favorable endpoint *and* the highest probabilities of success. But 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. It should be noted, however, that large disagreements among experts may indicate it is optimal to gather more information before proceeding to any large investments.

This elicitation was part of a larger project, covering seven technological categories 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.[11] 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 end-points. These facilitated expert elicitations that translate into economic cases for the members of this inter-related family of technology investments.

Acknowledgments

We thank the experts listed in Table 1. This research was partially supported by the Office of Science (BER) U.S. Department of Energy, Grant No.DE-FG02-06ER64203 and by NSF under award number SES-0745161.

[1] Searchinger, T., Heimlich, R., Houghton, R. A., Dong, F., Elobeid, A., Fabiosa, J., Tokgoz, S., Hayes, D., and Yu, T.-H. Use of u.s. croplands for biofuels increases greenhouse gases through emissions from land-use change. *Science*, 319:1238 – 1240, 2008.

[2] Pamela R. D. Williams, Daniel Inman, A. A. G. A. H. Environmental and sustainability factors associated with next-generation biofuels in the u.s.: What do we really know? *Environ. Sci. Technol.*, Forthcoming, 2009.

[3] Sagara, A. D. and der Zwaan, B. V. Technological innovation in the energy sector: R&D, deployment,and learning-by-doing. *Energy Policy*, 34:2601–2608, 2006.

[4] National Research Council. *Prospective Evaluation of Applied Energy Research and Development at DOE (Phase Two).* The National Academies Press, Washington D.C., 2007. http://www.nap.edu/catalog/11806.html.

[5] Apostolakis, G. The concept of probability in safety assesssments of technological systems. *Science*, 250:1359 – 1364, 1990.

[6] Cagno, E., Caron, F., Mancini, M., Palomo, J., Insua, D. R., and Ruggeri, F. Coping with historical reliability of expert elicitation in the integration of subjective judgements and historical data. In *Proceedings of the Second Annual Conference on Business and Industrial Statistics*, volume 2002, 2002.

[11] 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.

[7] Howard, R. A. Decision analysis: Practice and promise. *Managment Science*, 34:679–695, 1988.

[8] Clemen, R. and Kwit, R. The value of decision analysis at Eastman Kodak Company, 1990-1999. *Interfaces*, 31:74–92, 2001.

[9] Sharpe, P. and Keelin, T. How smithkline beecham makes better resource-allocation decisions. *Harvard Business Review*, 76, 1998.

[10] Thomas, H. Decision analysis and strategic management of research and development: A comparison between applications in electronics and ethical pharmaceuticals. *R&D Management*, 15:3–22, 1985.

[11] Howard, R. A., Matheson, J. E., and North, D. W. The decision to seed hurricaines. *Science*, 176:1191 – 1202, 1972.

[12] Morgan, M. G. and Keith, D. W. Subjective judgments by climate experts. *Environmental Science and Technology*, 29, 1995.

[13] Peerenboom, J. P., Buehring, W. A., and Joseph, T. W. Selecting a portfolio of environmental programs for a synthetic fuels facility. *Operations Research*, 37:689–699, 1989.

[14] Heinrich, G., Basson, L., Cohen, B., Howells, M., and Petrie, J. Ranking and selection of power expansion alternatives for multiple objectives under uncertainty. *Energy*, 32:2350 – 2369, 2007.

[15] Huang, J. P., Poh, K. L., and Ang, B. W. Decision analysis in energy and environmental modeling. *Energy*, 20:843–855, 1995.

[16] Baker, E., Chon, H., and Keisler, J. Advanced solar R&D: Combining economic analysis with expert elicitations to inform climate policy. *Energy Economics*, 31:S37 – S49, 2009.

[17] Baker, E., Chon, H., and Keisler, J. Carbon capture and storage: Combining expert elicitations with economic analysis to inform climate policy. *Climatic Change*, 96(3):379, 2009.

[18] Baker, E., Chon, H., and Keisler, J. NuclearPower: Combining expert elicitations with economic analysis to inform climate policy. Available at SSRN: http://ssrn.com/abstract=1407048, 2008.

[19] Baker, E., Keisler, J., and Chon, H. Battery technology for electric and hybrid vehicles: Expert views about prospects for advancement. *Technological Forecasting and Social Change*, 77:1139–1146, 2010.

[20] Winkler, R. L. and Clemen, R. T. Multiple experts vs. multiple methods: Combining correlation assessments. *Decision Analysis*, 1:167–176, 2004.

[21] Perdue, R. K., McAllister, W. J., King, P. V., and Berkey, B. G. Valuation of r and d projects using options pricing and decision analysis models. *Interfaces*, 29:57–74, 1999.

[22] Smith, J. E., Holtzman, S., and Matheson, J. E. Structuring conditional relationships in influence diagrams. *Operations Research*, 41:280–297, 1993.

[23] Spetzler, C. S. and von Holstein, C. S. S. Probability encoding in decision analysis. *Management Science*, 22:340–358, 1975.

[24] Carolan, J. E., Joshi, S. V., and Dale, B. E. Technical and financial feasibility analysis of distributed bioprocessing using regional biomass pre-processing centers. *Journal of Agricultural & Food Industrial Organization*, 5:1–27, 2007.

[25] Duffy, M. D. and Nanhou, V. Costs of producing switchgrass for biomass in southern iowa. In Janick, J. and Whipkey, A., editors, *Trends in New Crops and New Uses*, pages 267–275. ASHS Press, Alexandria, VA, 2002.

[26] Ajanovic, A. and Haas, R. Economic challenges for the future relevance of biofuels in transport in EU countries. *Energy*, 35:3340 – 3348, 2010.

[27] U.S. Department of Energy. Biomass multi-year program plan. *Office of the Biomass Program Energy Efficiency and Renewable Energy*, 2009.

[28] Hogarth, R. M. *Judgment and Choice*. Wiley, 1988.

[29] Clemen, R. and Winkler, R. Combining probability distributions from experts in risk analysis. *Risk Analysis*, 19:187–203, 1999.

[30] Kahneman, D. and Lavallo, D. Timid choices and bold forecasts: A cognitive perspective on risk taking. *Management Science*, 39, 1993.

[31] Tversky, A. and Kahneman, D. Availability: a heuristic for judging frequency and probability. *Cognitive Psychology*, 5, 1973.

[32] B. Fischhoff, P. S. and Lichtenstein, S. Fault trees: Sensibility of estimated failure probabilities to problem representation. *Journal of Experimental Psychology: Human Perception and Performance*, 4, 1978.

[33] Bonini, N. and Caverni, J. The "catch-all underestimation bias": Availability hypothesis vs. category redefinition hypothesis. *Current Psychology of Cognition*, 14, 1995.

[34] Tversky, A. and Kahneman, D. Judgement under uncertainty: Heuristics and biases. *Science*, 185:1124–1131, 1974.

[35] Hultman, N. E. and Koomey, J. G. The risk of surprise in energy technology costs. *Environmental Research Letters*, 2:1–6, 2007.

[36] Tichy, G. The over-optimism among experts in assessment and foresight. *Technological Forecasting & Social Change*, 71:341 – 363, 2004.

[37] Keith, D. W. When is it appropriate to combine expert judgments? *Climatic Change*, 33, 1996.

[38] von Winterfeldt, D. and Edwards, W. *Decision Analysis and Behavioral Research*. Cambridge Universtiy Press, Cambridge, U.K., 1986.

[39] Sims, R., Taylor, M., Saddler, J., and Mabee, W. From 1st- to 2nd-generation biofuel technologies - full report- an overview of current industry and RD&D activities. Technical report, International Energy Administration, 2008.

[40] NOAA. Restoration economics: Discounting and time preference, 2009. http://www.csc.noaa.gov/coastal/economics/discounting.htm.

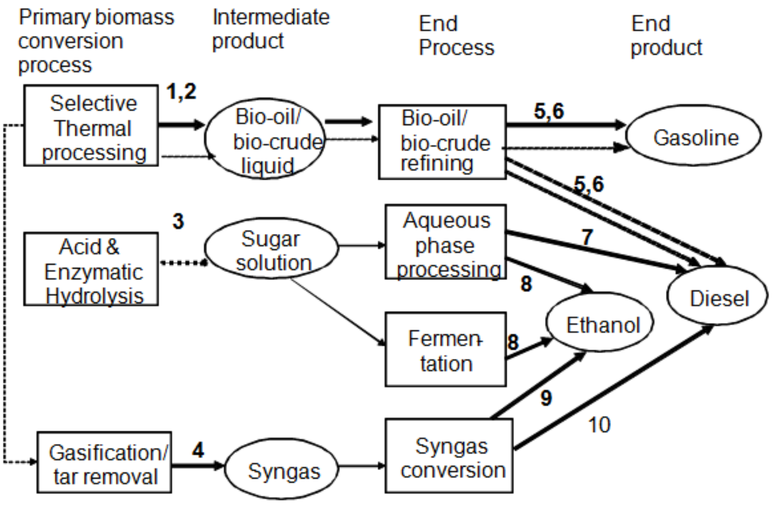


Figure 1: Technological paths from feedstock to end product

Expert	**Institution**
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

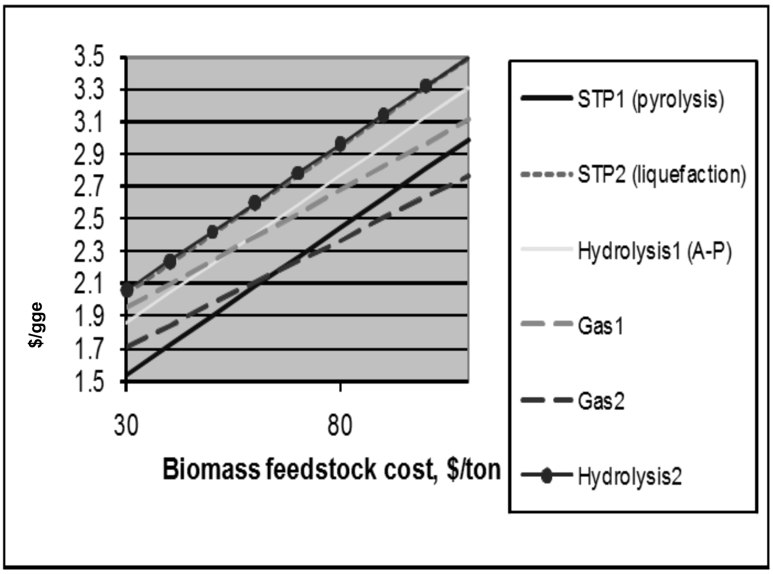


Figure 2: The cost per gge of each path as a function of the cost of the biomass feedstock

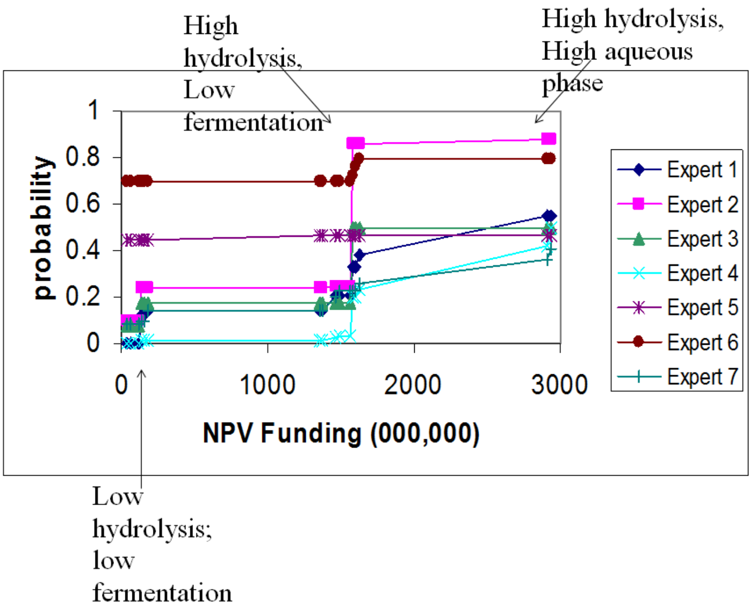


Figure 3: Probabilities of success for the hydrolysis paths

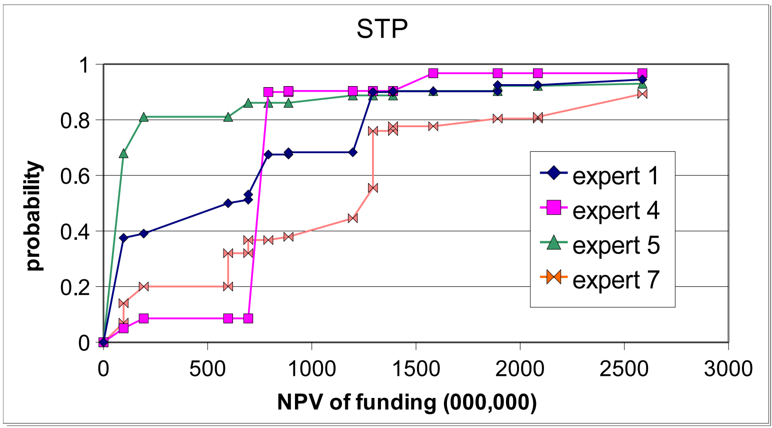


Figure 4: Probabilities of success for the STP paths

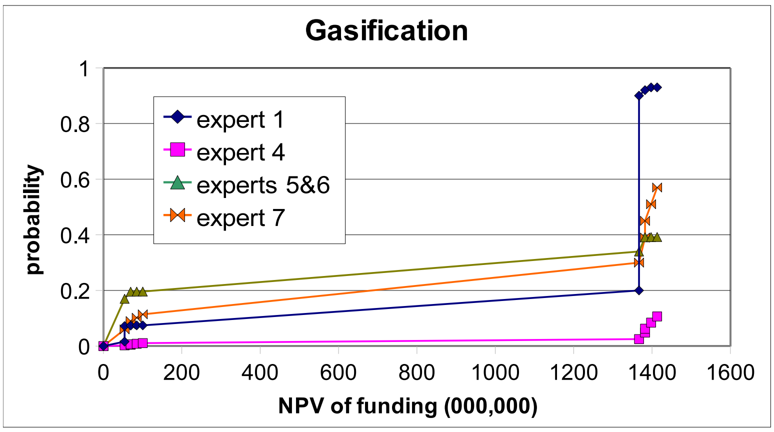


Figure 5: Probabilities of success for the gasification paths

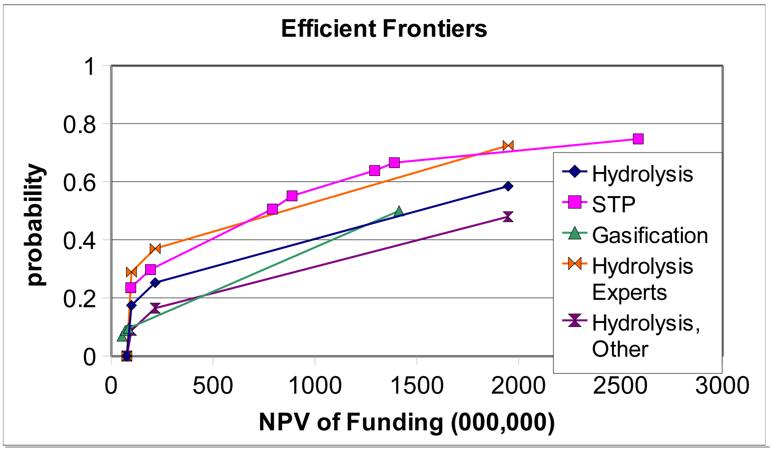


Figure 6: Efficient frontiers of the technology paths

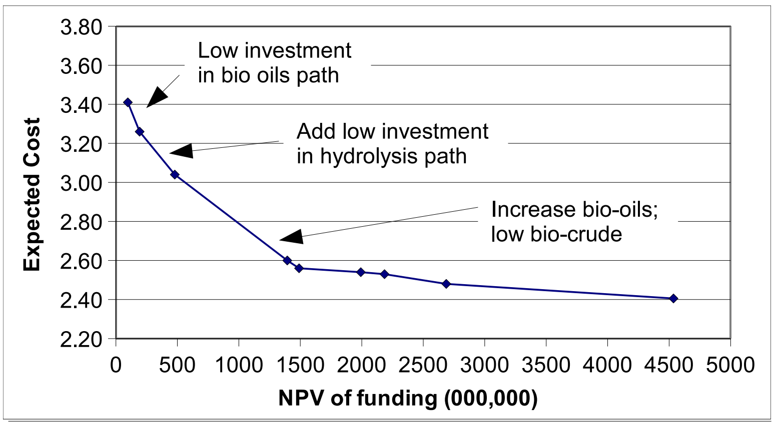
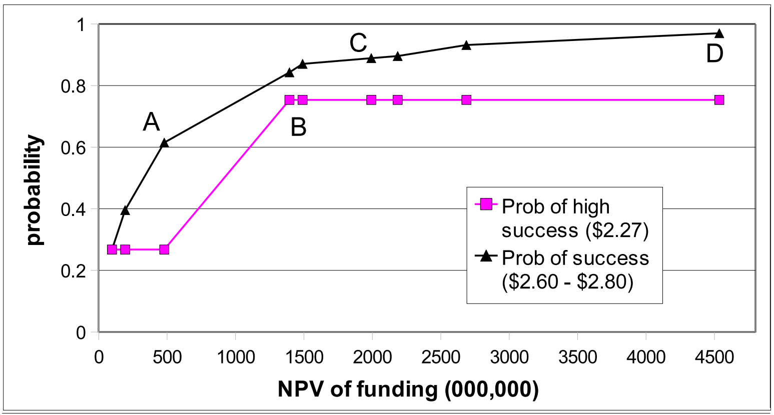


Figure 7: The expected cost of biofuels as a function of R&D investment. This assumed investment in the efficient portfolio.



A: Low investments in bio-oil, bio-crude, hydrolysis

B: High investment in bio-oil, low in hydrolysis

C: Increasing investment in bio-crude

D: Increased investment in hydrolysis

Figure 8: The probability of success for two success levels as a function of R&D investment. This assumed investment in the efficient portfolio.

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/ diesel gal ($0.40/L)		40%, 70%		
8 Fermentation	$1.0/ ethanol gal ($0.26/L)		320 Liters/ton		
9 Syngas to Diesel	$1/ gal diesel ($0.40/L)		55% (syngas energy)		
10 Syngas to Ethanol	$1/ gal ethanol ($0.26/L)		50%		

Table 2: Technological endpoints as defined for the elicitation.

Path	fuel	E	P	v	C (per gge)	C (per L)
STP1 (pyrolysis)	gasoline	40%	1	1	2.27	0.6
STP2 (liquefaction)	gasoline	40%	1.5	1	2.77	0.73
Hydrolysis1 (A-P)	diesel	40%	1.5	0.88	2.6	0.69
Gas1	ethanol	50%	1	1.52	2.53	0.67
Gas2	diesel	55%	1.5	0.88	2.25	0.59
Hydrolysis2	ethanol	320L/ton	1	1.52	2.79	0.74

Table 3: Estimated cost for the different technological paths. E is efficiency; P is processing cost; ν is conversion factor to gge.

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

	Liquefaction		Pyrolysis	
Funding Trajectory	Low	High	Low	High
Ex. 1	5%	50%	75%	100%
Ex. 2				
Ex. 3				
Ex. 4	75%	75%	100%	100%
Ex. 5	47%	60%	80%	90%
Ex. 6	20%	40%	25%	70%
Ex. 7	35%	80%	35%	93%
Average	36%	61%	63%	91%

Table 5: Elicitation results for first stage hydrolysis and pyrolysis technologies

	Hydrolysis			Gasification		
Funding Trajectory	No	Low	High	Low	Medium	High
Ex. 1		25%	66%	8%	100%	100%
Ex. 2	0%	25%	90%			
Ex. 3	0%	18%	50%			
Ex. 4		5%	80%	5%	50%	50%
Ex. 5	30%	40%	50%			
Ex. 6	0%	70%	80%	20%	40%	
Ex. 7	0%	25%	45%	15%	75%	95%
Average	6%	30%	66%	12%	66%	82%

Table 6: Elicitation results for first stage liquefaction and gasification technologies

	Aqueous Phase		Fermentation		
Funding Trajectory	Low	High	Low	Medium	High
Ex. 1	15%	50%	66%	50%	66%
Ex. 2	1%	50%	95%	95%	95%
Ex. 3	8%	45%	100%	100%	100%
Ex. 4	5%	50%	5%	25%	25%
Ex. 5	60%	75%	72%	72%	72%
Ex. 6	95%		90%	90%	90%
Ex. 7	30%	75%	20%	40%	60%
Average	31%	58%	64%	67%	73%

Table 7: Elicitation results for the second stage of hydrolysis paths

	Refine bio-oil		Refine bio-crude	
Funding Trajectory	Low	High	Low	High
Ex. 1	50%	90%	50%	90%
Ex. 2				
Ex. 3				
Ex. 4	5%	90%	5%	90%
Ex. 5	85%	93%	87%	95%
Ex. 6				
Ex. 7	20%	60%	40%	95%
Average	40%	83%	46%	93%

Table 8: Elicitation results for the second stage of STP paths

	Syngas to Diesel		Syngas to Ethanol	
Funding Trajectory	Low	High	Low	High
Ex. 1	90%	90%	20%	30%
Ex. 2				
Ex. 3				
Ex. 4	5%	10%	5%	13%
Ex. 5	85%	86%	85%	86%
Ex. 6				
Ex. 7	20%	40%	40%	60%
Average	57%	38%	47%	

Table 9: Elicitation Results for the second stage of gasification paths