Memo
To: RBAEF Participants, Mark Paster
By: Lee Lynd & Eric Larson
Subject: Mature technology
Date: December 4, 2003

I. Motivation and Introduction. We seek to identify and evaluate paths by which biomass can make significant improvements in the sustainability and security of energy supply and utilization in the United States. In so doing, we are emphasizing mature technology. Achieving a sustainable world, even by the most optimistic estimates, will take many decades. Thus the question of evaluating the potential role of a particular technology or resource in a sustainable world is necessarily a question about the relatively distant future. A lot of effort could be applied, and progress achieved, between now and then. In justifying such effort from a public policy perspective, it is much more important to consider the features of a technology that could eventually be realized rather than the features that are achievable today. Likewise, in assessing the potential contribution of a particular technology or resource to a sustainable world, it is as important to know where we can reasonably expect to get as to know where we are. In our opinion, mature technology scenarios have been under-utilized in energy planning and analysis of alternative energy futures.

Mature technology scenarios, however well-justified, should not be confused with technologies available for implementation today. Achieving performance and benefits associated with mature technology will require a large and focused effort over a period of time. Estimating features of mature technology is a separate matter from envisioning—much less enabling—one or more technical paths leading to mature technology, and is also separate from describing the societal transitions associated with adoption of mature technologies in lieu of technologies in use today. Significant transitions in the energy supply arena have always occurred over periods measured in decades in the past, and there is every reason to believe that this will be the case in the future as well.

Finally, it is important to acknowledge that there is inherent uncertainty in forecasting features of mature technology, regardless of the approach taken in the effort. This uncertainty is present both with respect to individual technologies and also with respect to comparison among mature technology scenarios for two or more technologies. With a systematic approach such as that presented in this memo, we are seeking to avoid some errors associated with comparing technologies at different levels of maturityand to achieve some degree of standardization among mature technology scenarios. Indeed, application of a systematic approach to estimating features of mature technologies across a variety of technologies is an important distinguishing feature of the RBAEF project.

II. R&D Strategy. Two key elements of a productive approach to meeting energy sustainability and security challenges are, in our view:

1) Identify technologies that have potential, upon completion of a specified R&D path, to make significant contributions to meeting demand for energy services in conjunction with societal objectives including sustainability, security, and economic feasibility;

2) Aggressively pursue research and development on most if not all technologies in this category in order to advance them toward commercial readiness and to increase the certainty with which performance and cost can be estimated.

With respect to item 1), it is desirable to define potential according to whether a technically sound argument supported by rigorous analysis is made by a knowledgeable advocate, even if not all are equally optimistic about the probability of success. There will always be doubters, and the ideas that prove to be the most significant often have more than their share of critics because they deviate from accepted paradigms. With respect to item 2), we acknowledge that a truly comprehensive R&D program in which promising technologies are aggressively pursued at the level of research, and piloting where appropriate, would likely cost substantially more than is allocated to energy R&D today in the U.S. However, increased funding for energy R&D is sorely needed and long over due[*]. Moreover, we think it very likely that a comprehensive R&D effort directed toward sustainable and secure energy sources would be imminently affordable and, if effectively administered, pay rich dividends.

III. Operational definitions. In discussions with project members, experts in processing and downstream mobility chain technologies seem much more comfortable with the notion of approaching an asymptotic limit as compared to experts in feedstock production. Consistent with this observation, we have decided to use somewhat operational definitions of mature technology in these two contexts:

- *Feedstock production*. For development of cellulosic energy crops and practices related to their cultivation, mature technology for the purposes of this project will denote an expended effort and state of advancement comparable to that for corn production today.
- *Processing and downstream mobility chain technologies*. For biomass processing and mobility chain technologies (energy carrier distribution, delivery, storage, vehicles), mature technology for the purposes of this project denotes a state of advancement such that additional R&D effort would offer only incremental improvement in either cost or benefit realization.

IV. Elaboration of the mature technology concept.

A. Need for consistent cost accounting. The estimated cost of any processing facility, regardless of its state of maturity, can be strongly impacted by parameters of the cost database and framework used. Such parameters include the cost of equipment (bare module cost), the cost of installation, return on investment, instrumentation and piping allowance, overhead, construction and start-up time, maintenance, depreciation, assumed tax rate, business expenses, owner's cost and profit, and working capital. Different allowances for these factors could conceivably lead to large differences in the estimated cost of two identical facilities evaluated within different costing frameworks. Thus there is a strong need for consistent cost accounting when comparing different technologies.

B. Need to consider the same cost-impacting factors. The cost of energy services delivered by mature technology is considered here, recognizing that features in addition to cost (e.g. efficiency, pollution) are also of interest for our project. Table 1 lists categories of cost factors applicable to a technology as it progresses from initial conception to maturity. When analyzing mature configurations of different technologies, care should be taken to ensure that

[*] As observed in 2001 by noted energy expert John Holdren: Current levels of public and private investment in energy R&D and demonstration are not remotely commensurate with the long-term challenges and opportunities, either in the United States or in any other country. U.S. federal expenditures on applied energy technology R&D are about what they were, in real terms, just before the oil price shock of 1973-1974, although the country's economy is more than twice as large [and, we add, the impetus to develop sustainable and secure energy supply technologies is much more compelling]. U.S. private sector investments in energy R&D have been falling since the mid-1980s.

the same categories of cost reduction factors are considered for each technology. The selling price impact of the factors examined in Table 1 is schematically represented in Figure 1.

Table 1. Factors impacting the cost of processing facilities in relation to technological maturity.

1. Pre-commercialization (from the first estimate to the first commercial plant).

Pre-commercial cost growth. Costs of pioneer commercial facilities tend to be higher than anticipated due to a variety of factors. These include processes that become more complicated or perform less well than first envisioned. In addition, preliminary cost estimates are often made on an "nth plant" basis and the cost of first plants are markedly higher as described below. The often-quoted "Rand Study" of 1981 found that costs of pioneer plants in the oil, chemical, and minerals industries exceeded initial cost estimates by an average of 2.7-fold.

2. Post-commercialization (after the first plant is built).

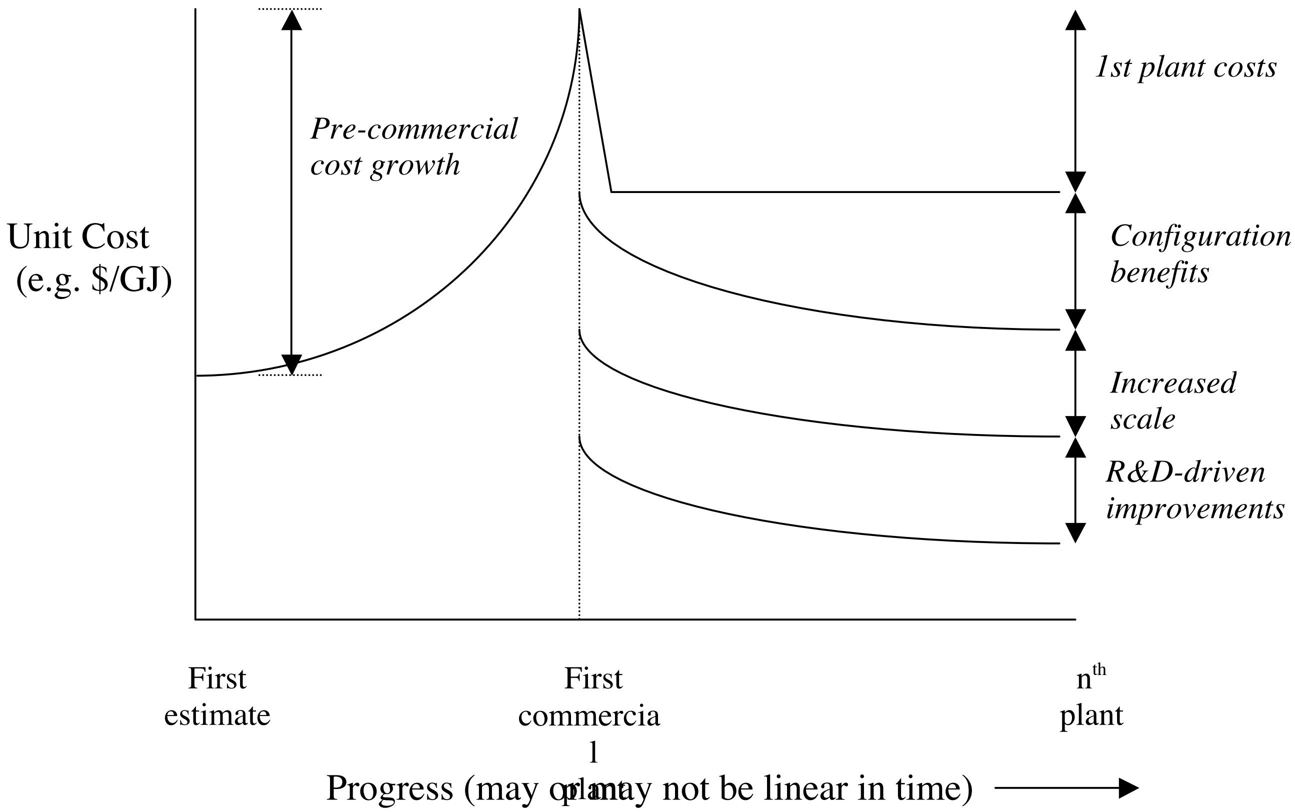
a. 1st plant costs. The cost of a first-of-a-kind processing facility is markedly higher than the cost of a second facility relying on the same technology, even in the absence of cost reductions associated with configuration benefits, increased scale, and R&D-driven improvements (see below). Such "first plant costs" arise from a high cost of capital (the actual cost of raising a dollar spent on plant capital), longer construction lead times (with consequent negative impacts on discounted cash flow), and conservative design assumptions (which cause first-of-a-kind plants to be more expensive).

b. Configuration benefits. In the cost of building successive plants with essentially the same process technology, cost benefits are typically realized as a result of factors such as better integration among different unit operations (process steps), including elimination of redundant or over-designed components, and de-bottlenecking. As used here, realization of configuration benefits does not require R&D-driven advances that lead to improvements in the unit operations comprising a process, although this distinction if more clear-cut for some technologies than for others.

c. Increased scale. Economies of scale (less cost per unit output at greater scale) are realizable over the range of biomass feedstock supply rates commonly considered (e.g. up to 1000 tons per day), but also at much larger scales. Although feedstock costs increase modestly due to increased transport radius for larger plants, both Marrison and Larson (1996) and Wyman (2003) have found this increase to be smaller than the cost savings that can be realized from larger conversion facilities up to very large scales.

d. R&D-driven improvements. R&D-driven improvements as defined here lower the cost by reducing the cost of individual unit operations, and are thus distinct from savings due to configuration benefits which are realized at the level of integration among unit operations. Specific R&D-driven advances can take many forms, with examples being an improved catalyst, reactor system, or separation device. If such an advance enables consolidation of process steps that were formerly separate, this is classified as an R&D-driven improvement rather than a configuration benefit because an R&D-driven advance is required.

Figure 1. Illustration of the impact of different maturation-related cost factors on unit cost (values shown are hypothetical and not to scale)



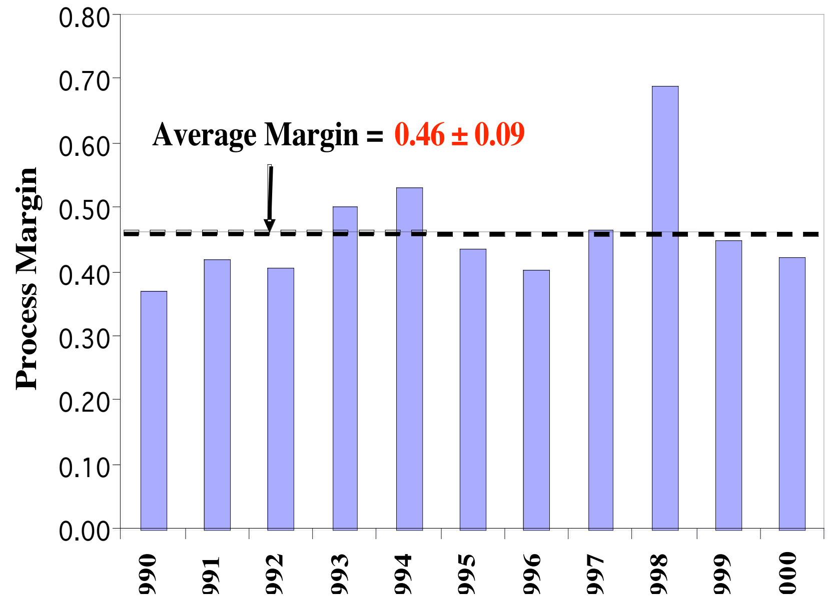
C. Calibration relative to existing mature technologies. Existing mature technologies can, in some cases, provide a valuable calibration standard for forecasts of potential improvements to currently immature technologies. For example, consideration of the cost margin, representing the ratio of value realized to the cost of raw materials, provides a framework for evaluating the status of a given technology relative to the margin of existing mature commodity processes. For this purpose, the relative process margin, M_R, can be defined as

$$M_R = \frac{V - (F + E)}{F + E} \qquad [1]$$

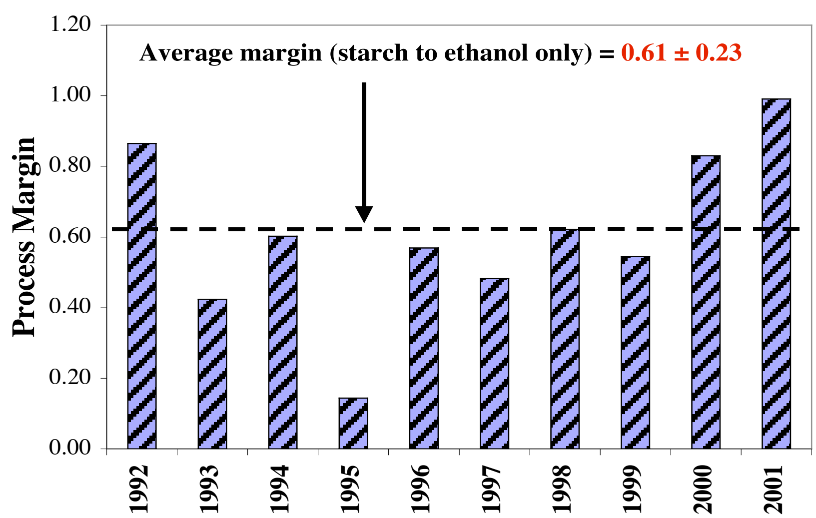
where V denotes the value of all products sold, F denotes the cost of the primary feedstock, and E denotes the cost of purchased, externally-produced process energy, all in the unit of $/ton feedstock. Figures 2A and 2B show M_R vs. time data for two mature refining processes: oil refining and production of ethanol from corn (values shown are for wet milling but are very similar for dry milling).

Figure 2. Relative process margin for petroleum refining and ethanol production from corn..

A. U.S. Petroleum refining, 1990-2000 (API, 2001; EIA, 2001; Oil & Gas Journal, 2002)



B. Ethanol production from corn. (Corn Refiners Association, 2001; Nebraska Ethanol Board, 2002.



The average process margin is 0.46 for petroleum refining, and 0.6 for corn ethanol production. These values suggest a possible "rule of thumb" that mature, economically feasible processes producing fuels on a very large scale are characterized by processing margins of around 0.5.

While of potential value, use of processing margins also has some limitations that should be realized. Among these are the following:

- A given candidate process does not necessarily have the potential to become economically feasible, and thus to realize process margin values consistent with existing processes.
- Similar relative process margins may mask absolute differences in processing costs due to different feedstock costs. It happens that both oil and corn have similar purchase prices on an energy basis (on the order of $5/GJ). If some other feedstock had a significantly different purchase price, then a similar relative process margin implies quite different actual processing costs on a per unit feedstock basis.

V. Basis for estimating features of mature technology. Consistent with the R&D strategy articulated in Section II, performance parameters in this study are selected according to *a knowledgeable optimist's most likely estimate*. This is neither the optimist's best case estimate, nor the average most likely estimate of experts spanning the optimist-pessimist spectrum.

The importance of energy-related challenges together with the relatively modest cost of R&D suggests that a comprehensive approach aimed at not missing potential breakthrough opportunities is preferred over advancing only a few approaches or proceeding only when there is consensus among experts (see Section II).

VI. Recommendations and Limitations Relative to Cross-Technology Comparisons. When making comparisons about estimated features of different currently immature technologies in the mature state, it is possible and desirable to ensure that the following conditions be satisfied:

- Consistent operational definitions are applied (e.g. III above).
- A consistent cost accounting framework is applied (see IV.a)
- The same cost impacting factors are considered (see IV.b. above)
- Calibration with existing mature technologies is undertaken where possible (see IV.c. above).
- A common approach for estimating features of mature technology is used (e.g. see V above).
- The importance of various assumptions in relation to overall metrics (e.g. cost, efficiency) are explored and presented using sensitivity analysis.

There have been few studies of mature technology undertaken in general. There have been many fewer, and possibly none, that have satisfied the five conditions listed above.

Meeting the conditions listed in the previous paragraph goes a long way toward framing a useful mature technology analysis. However, it is also important to recognize that :

- The potential for R&D-driven improvement (e.g. cost reductions) may not be the same for different technologies;
- The certainty with which R&D-driven improvement can be anticipated may not be the same for different technologies. This applies both to the magnitude of benefits from foreseeable advances as well as the occurrence and benefits associated with unforeseen advances.

- The extent of optimism inherent in expert estimates may not be the same for different technologies.

Because of these observations, it is not possible to be sure that estimates of the features of two different currently immature technologies in the mature state will incorporate the same degree of optimism and have the same probability of being realized. This limitation should be borne in mind when considering the results of mature technology analysis. It should also be realized that the problem of calibrating the extent of technological maturity, the degree of optimism, and the probability of realization is not limited to mature technologies, but applies to both inter- and intra-technology comparisons involving supposedly "current" technologies as well.

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