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Q31 Advanced biofuels from pyrolysis oil...Opportunities for cost reduction

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ABSTRACT

Hydrocarbon derived from fast pyrolysis of plantation wood is a potential feedstock for the production of 21 transportation fuels. Unfortunately, the cost to produce and upgrade this feedstock is highly uncertain, and 22 its current technological state is not competitive with crude oil. Additional R&D will be needed to achieve 23 the significant cost reductions required for competitiveness. Significant technical hurdles must be overcome 24 to achieve a commercially ready, cost competitive technology. This paper identifies the most promising areas 25 for the needed future research. Identification of a stable upgrading catalyst, definition of the maximum level 26 of oxygen that can be tolerated by the existing refining infrastructure, and improved oxygen removal during 27 the pyrolysis step emerge as the most prospective research areas. 28

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34 1. Introduction

Several alternative processes are being developed to produce biofuels 35 from non-edible biomass. They generally fall into one of three categories: 36 1) biochemical routes to sugars ending with either fermentation to form 37 an alcohol fuel or catalytic conversion to produce conventional fuels, 38 2) gasification followed by biochemical conversion of synthesis gas into 39 motor fuels or alcohols, and 3) fast pyrolysis followed by hydro process- 40 ing, which is the topic of this study [1]. Plausible cases have been made 41 that each of these routes can produce transportation fuels from biomass 42 at competitive costs in the future. All are still in development and none 43 have demonstrated competitive economics versus conventional hydro- 44 carbons on a commercial scale. Early operators of each technology will 45 be challenged by the uncertainties and costs associated with pioneer 46 plants. The likely range of costs show substantial overlap given the cur- 47 rent state of each technology. Fast pyrolysis is the least developed of the 48 potential methods to convert woody biomass to transportation fuels 49 and is characterized by more uncertainty but also more potential. A re- 50 cent study comparing alternative processes, using corn stover as feed- 51 stock [2] showed fast pyrolysis to be the least capital intensive and 52 most economical, principally due to the lower complexity of the tech- 53 nology. Its potential to produce conventional motor fuels and to make 54 use of existing refining and logistics infrastructure add to its potential 55 attractiveness. 56

Biofuel volumes mandated in the Energy Independence and Security 57 Act of 2007 (EISA) are the primary driving force for using pyrolysis oil 58 (Pyoil) to make transportation fuel. In a recent study [3] it was estimated 59

that the forest resources and refining concentration located in the South 60 Central United States have the potential to support a mature Pyrolysis 61 Oil industry producing a significant portion of the mandated "Advanced 62 Biofuel" volumes. It is estimated that this region alone could support 63 motor fuels production from Pyoil of 500 kbd or more. Other parts of 64 the U.S. could also support Pyoil value chains, albeit with economics less 65 favorable than the South Central region, and could add to this projected 66 volume. 67

Pyoil's ultimate appeal to the U.S. refining industry will be based upon 68 its becoming an inexpensive feedstock relative to crude oil and/or other 69 renewable fuels. This may be achieved over the course of the time as a re- 70 sult of several factors. 71

Many refiners believe that crude oil will be increasingly supply 72 constrained. This condition could systematically raise crude oil's cost in 73 real terms. The Pyoil feedstock, wood biomass, should not see its costs 74 materially linked to that of crude oil. Some petroleum fuel is consumed 75 in harvesting and logistics, but much of wood biomass production cost 76 involves capital tied up in land/trees and the time value of money be- 77 tween planting and harvest. Thus, refiners can look at wood biomass as 78 a feedstock source largely de-linked from crude prices. Wood biomass 79 should therefore become increasingly economic relative to crude over 80 time. The key question is when will this occur. Successful cost reduction 81 R&D will shorten the time when this will occur. 82

2. Methodology 83

The purpose of this paper is to define research areas that have the 84 largest potential impact for reducing the cost of bio-crude from fast py- 85 rolysis of wood. In discussing research opportunities, it is useful to define 86 a base case value chain. For this study the configuration and economics of 87

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the Mature Industry value chain summarized in a recent study [3] will be used (the biomass source is plantation wood shipped via barge to integrated pyrolysis and upgrader plant located on the lower Mississippi River with an overall plant capacity of 20 thousand dry tons/day (kt/d dry) of wood consisting of four 5 kt/d pyrolysis reactors and a single upgrader reactor). Fig. 1 summarizes the value chain and shows the relative contribution of each step.

This case takes maximum advantage of economies of scale, high concentration of biomass, availability of low cost transportation and location in region of high concentration of refining capacity. Note that this case assumes that successful scale up of pyrolysis reactors to 5 kt/d has been achieved (current technology uses 200 t/d reactors) and that a fixed bed reactor is used for the upgrader (a stable upgrader catalyst is found). Failure to scale the pyrolysis reactors to this size and/or having to use a more complex upgrading reactor (cyclic or moving bed) would lead to a higher overall value chain cost but should not materially change the results of this study.

In considering various research opportunities, the following adjustments were made. Where changes were made to capital investments the investment related costs are adjusted via $(\text{capacity})^{0.60}$ for the upgrader and via $(\text{capacity})^{0.7}$ for the pyrolysis unit except for the pyrolysis reactors. For the pyrolysis reactors, the investment related costs were adjusted via $(\text{capacity})^{0.7}$ up to a capacity of 5000 tons/day.

Above this level, parallel trains for reactors were assumed. In terms of adjustments for upgrader product oxygen levels, 1st order kinetics was assumed and only the upgrader reactor investments were affected. The hydrogen consumption was adjusted using the Veba data [4] for upgrading levels other than the base case.

Given that there is a high degree of uncertainty for the capital and total value chain costs, the research opportunity areas were tested with a range of investment cost bases (Pioneer Plant vs. n -th plant based contingencies) and are expressed as percentage reduction in total value chain costs. The RAND [5] methodology was used to adjust the upgrader and pyrolysis investment for the pioneer plant cases reflecting the current uncertainties in the technology. As it turns out, while the absolute costs are significantly affected by the contingency values assumed, the percentage changes by research area are relatively insensitive to these uncertainties and for purposes of this study are virtually identical. Note that all the incentives reported here are not debited for the costs for effecting the potential improvements and therefore represent the maximum incentives available.

3. Results

As reported separately [3], the value chain cost range for the refined product entering the existing fuel distribution system would

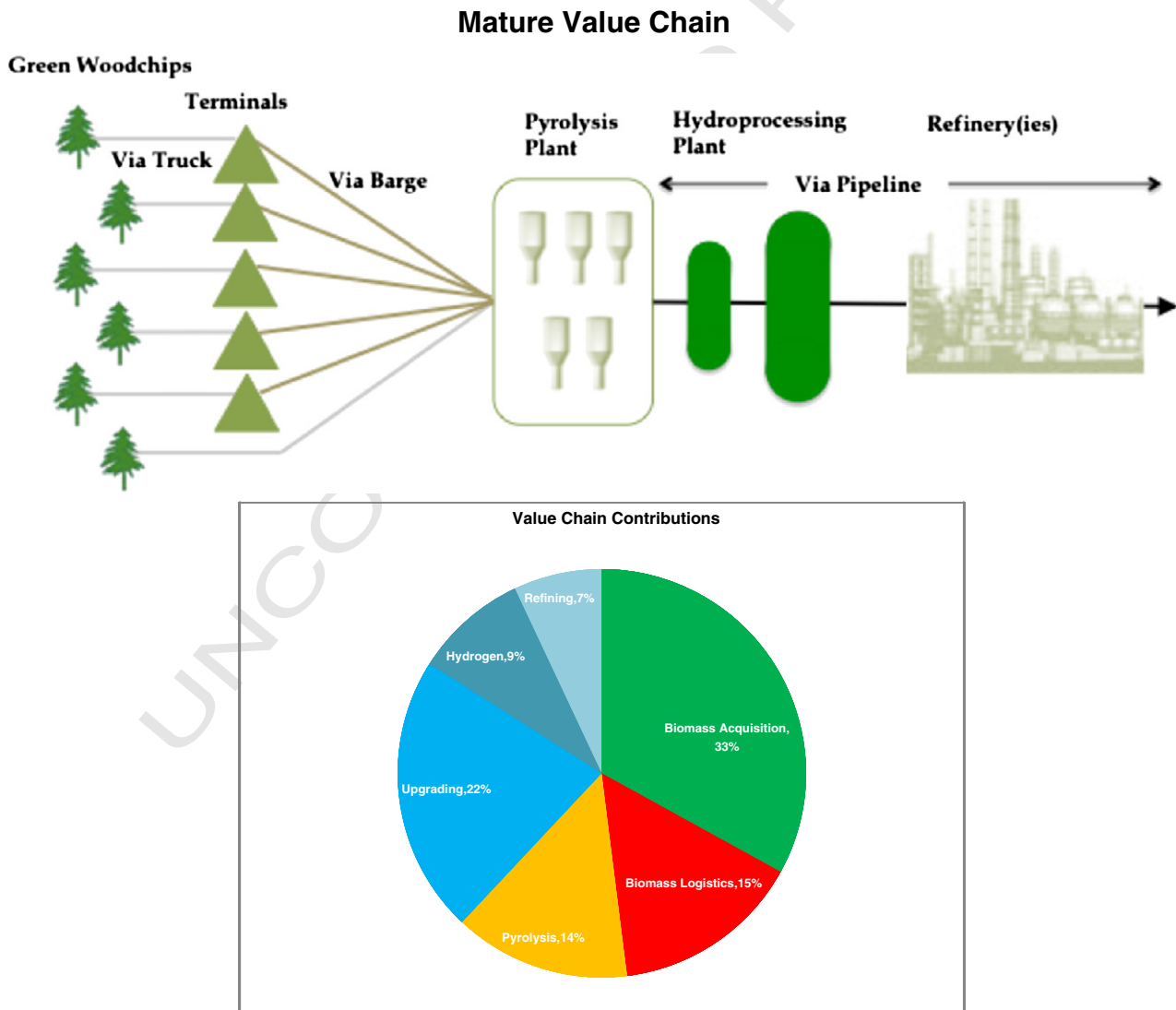


Fig. 1. Mature value chain.

be 3.75 to 5.25 \$/gallon based on today's technology. The estimate was made considering only performance that had been demonstrated at the time of this study (200 t/d pyrolysis reactors, recently reported pyrolysis and upgrader yields) and with favorable assumptions about corrosivity of upgraded pyrolysis oil and successful development of an upgrader catalyst system with a one year life. While highly uncertain, these results would suggest that improvements of up to 40% may be needed to bring this technology to be competitive with current petroleum prices. While some of the economic improvements will come from successful scale up of pyrolysis and upgrader reactors and are estimated to be about 20%, additional improvements of 20% in the base technology will be needed to close the gap [3].

Fig. 2 summarizes the results of this study. Given that these are maximum incentives, and do not include the costs required to affect these improvements, one broad observation is that all the potential improvement steps are relatively modest. There does not appear to be a single area of research that emerges that will yield a step change in costs. Rather a combination of improvement steps will be needed.

In looking at the specific R&D areas, upgrader catalyst stability and optimization of upgrader/refinery interface emerge as the ones with the highest priority. Both areas are characterized by large number of uncertainties, but significant potential economic impact.

The viability of the entire value chain is dependent on finding a stable upgrader catalyst. If a catalyst is not identified with life long enough for use in a fixed bed reactor, then the cost and complexity of the process increases. This is because more complex reactor systems must be considered such as cyclic or moving beds. This will increase the cost of the value chain and increase the complexity and cost of the overall development of the technology. These kinds of reactors would also require that the upgrading catalyst be regenerable.

There has been little work done to define the allowable Pyoil oxygen content that the existing refining infrastructure can handle. It appears there are significant cost optimization opportunities at the upgrader/refinery interface. In particular, partial upgrading shows some of the larger incentives identified in this study. This important but complex area will need to be explored at some point before this value chain can be commercialized.

Pyrolysis oxygen removal, plantation and upgrader / pyrolysis yields are the next most attractive areas for work. The areas of upgrader catalyst selectivity/activity and individual biomass cost reduction steps appear

to have smaller effect on costs. The challenge in all these potential research areas is finding low cost improvements that will not significantly erode the incentives shown above.

4. Discussion of results

4.1. Hydrotreating improvements

The hydrotreater represents one of the higher cost areas in the value chain and improvements here could have a significant cost impact. Catalyst activity, stability and hydrogen selectivity all represent potential improvement areas (upgrader yield is covered separately below). Catalyst stability stands out as a key research area. Currently available catalysts have poor stability, and unless significant progress is made in finding a stable upgrading catalyst, fuel products from Pyoil are unlikely to progress to commercialization.

Upgrader catalyst stability is the key uncertainty in the whole Pyoil value chain. The base case value chain discussed in this article assumes a one year upgrader catalyst life and this allows the use of a fixed bed reactor system. There are indications in the literature that current catalyst stability is poor and, moreover, the high hydrothermal conditions in the reactor represent a significant challenge for the integrity of the catalyst support [6]. In fact, there does not appear to be any data in the publicly available literature supporting a Pyoil upgrader catalyst with a multi-month catalyst life. The economics turn out to be particularly sensitive to catalyst life as shown in Fig. 3.

As can be seen, the cost is particularly sensitive to a catalyst with a life less than a year. This is because shorter catalyst life translates not only into higher catalyst costs but also has a significant impact on the service factor of the plant. The base case assumes a service factor of the process to be 90%. If one assumes that it takes two weeks to replace the catalyst, the service factor deteriorates to 86% if the catalyst life is 6 months and to 78% for a 3 month catalyst life. These calculations assume that the other items which contribute to the service factor remain unchanged. Realistically, one would not consider a fixed bed reactor system, if the catalyst life was, in fact, three or 6 months. At this point, other reactor types, such as a cyclic or moving bed, would have to be considered. In these cases, the catalyst would likely need to be regenerable. This change in reactor type would increase the cost and complexity of the process. In addition, the scale up of the process would

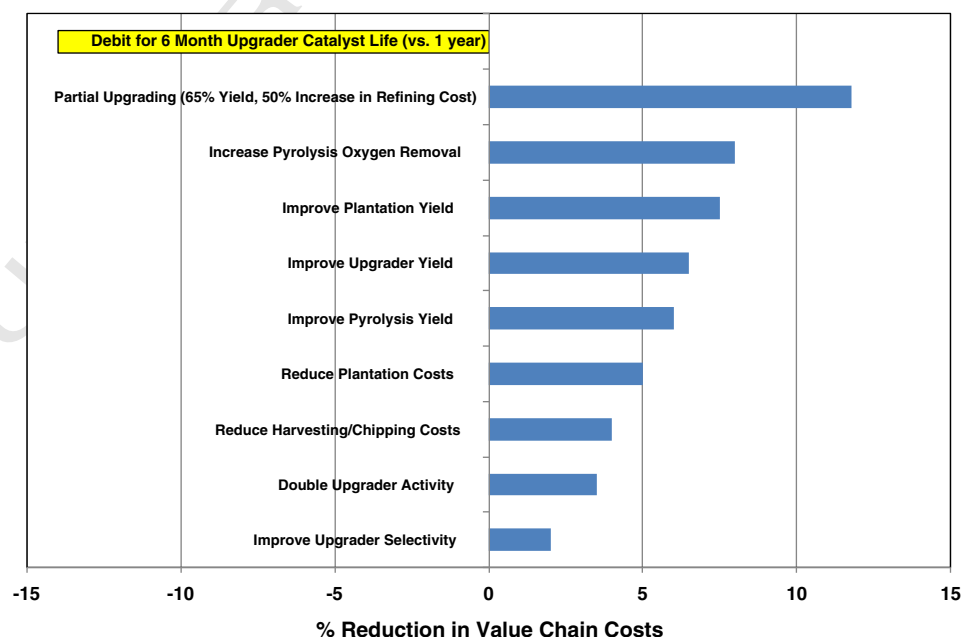


Fig. 2. Summary of research incentives.

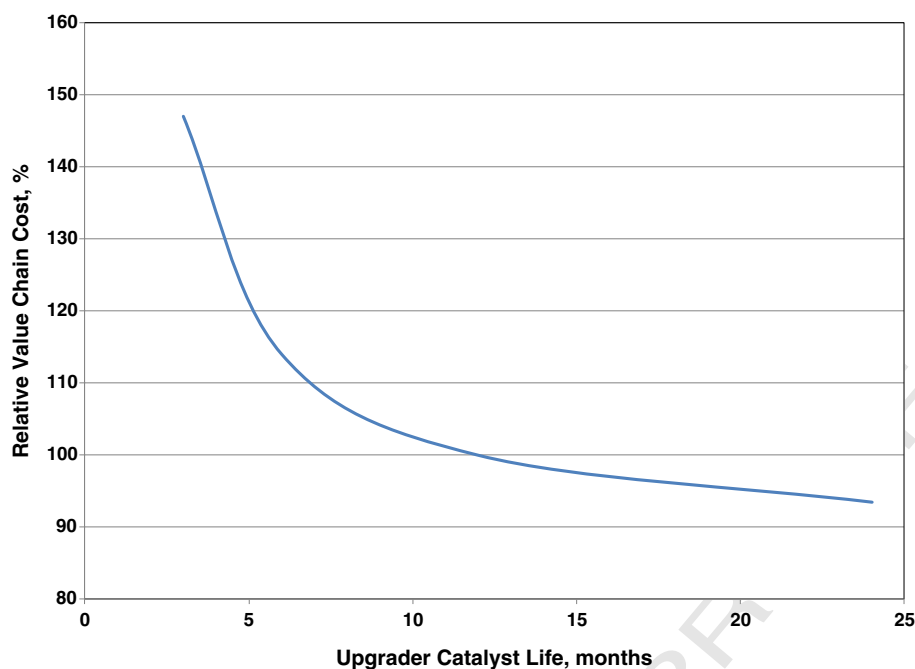


Fig. 3. Impact of upgrader catalyst life on costs.

become more costly and time consuming. It should be noted that the incentive for increasing the catalyst life beyond one year diminishes for a catalyst life greater than one year (7% reduction in value chain cost for a catalyst with a two year life). This overall discussion leads to the specific research objective for the upgrader; find a catalyst with at least a one year life.

It is found that catalyst activity and hydrogen selectivity have relatively smaller impacts on costs.

Doubling the activity surprisingly only improves the economics by about 2–5%. This is because only the reactor portion of the upgrader investment is impacted. If it assumed that the base case catalyst affects some excess hydrogenation of aromatic structures, then there may be an opportunity to develop a more selective catalyst with reduced hydrogen consumption and aromatic saturation. For example, if a 25% reduction in hydrogen consumption (reduce H/C of upgraded Pyoil from 1.75 to 1.33) could be affected, it would be worth about a 2% reduction in costs (the net hydrogen cost which includes some off gas credits represents about 8–10% of the total value chain costs in the base case.)

4.2. Oxygen removal options

Hydrotreating costs are very sensitive to the degree of upgrading required as shown in Fig. 4.

This chart highlights the importance of establishing the minimum level upgrading required because of the high cost of removing the last increment of oxygen. In looking for cost reduction opportunities, it is useful to look both upstream and downstream of the upgrader in the value chain. Two potential research areas are highlighted on the chart; greater oxygen removal in the pyrolysis step and partial upgrading combined with utilization of the hydrotreating capacity in existing refineries. The key question for each of these areas of research is how these approaches to oxygen removal compare in terms of cost with the base case of severe hydrotreating.

4.2.1. Partial upgrading / oxygen tolerant refining

The base case in this study assumes that the refinery can handle an upgrader Pyoil containing 0.2% oxygen. Unfortunately, there is very little information on the maximum level of oxygen that can be handled in the refinery processes and products, and what the associated costs are for

refining this material. This area has received little attention to date and will have to be addressed at some point if the pyrolysis route to fuels is to be developed. As will be shown below, there could be a large payout in optimizing the upgrader/refinery interface.

To define the maximum level of oxygen allowed in existing refineries, one needs to define (1) the corrosion/fouling properties of upgraded Pyoil as a function of oxygen level and boiling point, (2) the impact of oxygen on the refinery processes, particularly those with sensitive catalysts, and (3) the impact of Pyoil oxygen on gasoline and diesel product quality. Conceptually, what one is trying to do here is to utilize some of the existing refinery hardware to reduce the Pyoil upgrader severity and investment. Also, the use of the refinery's hydrotreating capabilities which are tailored for specific boiling ranges should potentially improve yields and better utilize hydrogen vs. using the single high pressure upgrader.

The sensitivity of the value chain economics to the allowable refinery oxygen level is significant. Given the high cost of removing the last increment of oxygen (Fig. 4), steps which enhance a refinery's ability to tolerate some oxygen in the feedstock could have a significant payout. The key issue is to define the oxygen level where acidity is low enough for safely introducing Pyoil into the refinery. To scope this issue, a brief analytical research was made in the course of this study [3]. Samples of Pyoil^a upgraded to three oxygen levels (8.2%, 4.9% and 0.4% oxygen) were cut into typical refinery fractions and subjected to standard "crude assay" tests.

The results of this initial testing were somewhat surprising. It was observed that for a Pyoil sample upgraded to 4.9% oxygen, the acidity of the heavy fractions (360–1050 °F) was very low as measured by total acid number (TAN).^b The acids appeared to congregate in the light fractions where they are potentially easier to treat. These promising acidity results will need confirmation because they are based on a single set of retained pilot plant samples using only TAN measurements as an indicator of acidity. A more detailed follow-up program on this lead has been developed and is reported elsewhere [3]. This additional testing should pay particular attention to the effects of aging on the pyrolysis oil

^a Samples were provided by PNNL from past runs.

^b Total acid number (the amount of potassium hydroxide needed to neutralize acid in the oil) is used by refiners to indicate the corrosion potential of a crude.

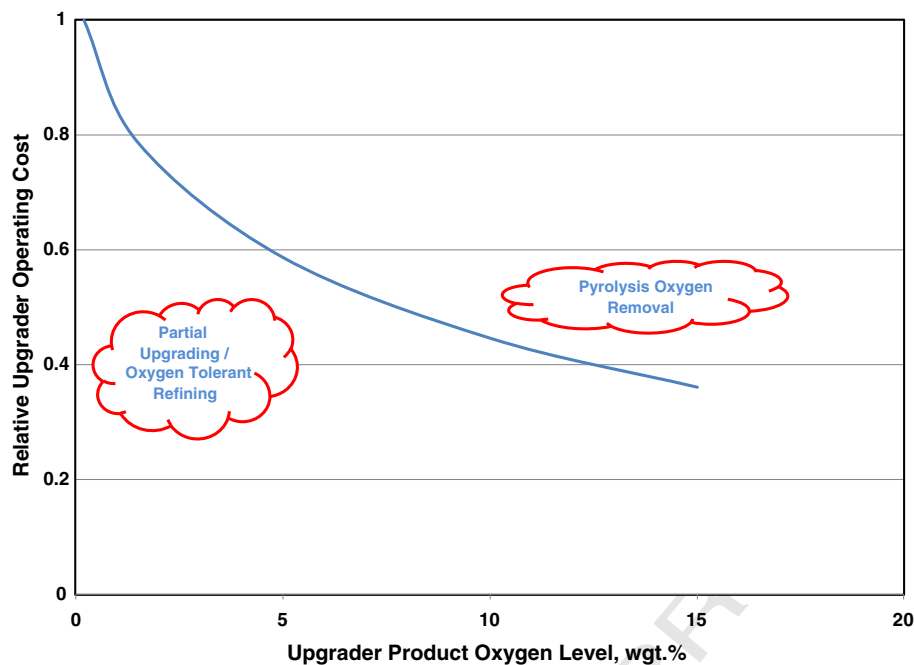


Fig. 4. Relative upgrading costs vs. upgrading level.

280 samples. If these unusual results are confirmed, actual corrosion work on
 281 the heavy fractions would be needed. It should be recognized that while
 282 TAN is useful as an indicator of corrosion for petroleum streams based on
 283 a large amount of experience and data, no such corresponding experi-
 284 ence base exists for Pyoil. The primary acids in petroleum are naphthenic,
 285 whereas after extensive upgrading of Pyoil the surviving oxygen
 286 species are largely phenolic acids [6].

287 These results suggest a strategy of partially upgrading Pyoil to only
 288 5% oxygen, separating out the 360+ deg F material, which is fed directly
 289 to a refinery, while further upgrading the light fractions, (light straight
 290 run (LSR) and naphtha) to reduce their acidity for safe introduction
 291 into the refinery. It was found that the light fractions of the sample
 292 upgraded to 0.4% oxygen had very low acidity (TAN was below detec-
 293 tion). It is not known what oxygen level (between 4.9% and 0.4%) in
 294 this fraction needs to be to have a TAN low enough for introduction
 295 into the refinery. Fig. 5 summarizes this approach. It is estimated that
 296 this partial upgrading option would significantly reduce upgrader reac-
 297 tor volume (48% of base case) and hydrogen consumption (68% of base
 298 case).

299 It turns out that two factors are very important in determining overall
 300 attractiveness of this approach; (1) the Pyoil yield from this configura-
 301 tion and (2) the incremental refining costs for treating this more difficult
 302 feed.

303 The economics were tested for a range of partially upgraded (5%
 304 oxygen) Pyoil yields. If one assumes the yield loss in upgrading to
 305 5% oxygen is all due to oxygen removal (no light ends loss due to hy-
 306 drocracking), the yield out of the upgrader would be 69% (neglecting
 307 any change in the H/C ratio of the upgraded Pyoil). The distillation
 308 curves of the three samples in this analytical study mentioned above
 309 suggest that significant hydrocracking does not occur until upgrading
 310 to between 5% and 0.4% oxygen. The general shape of the hydrogen con-
 311 sumption curve also supports this assumption. On the other end of the
 312 spectrum, if cracking to light ends is assumed to be a function of oxygen
 313 removal, then the yield would be closer to 57%.

314 Finding an optimal refining strategy then becomes a significant
 315 cost saving opportunity. For this study, the output of the refinery is
 316 sumed to be only transportation fuels ex-jet fuel. It was judged that
 317 the certification process to make jet from Pyoil based material was too
 318 problematic for this study. In terms of the refining of these two streams,

319 the initial thinking is to feed Stream A^c to the naphtha hydrotreater plus
 320 reforming/isomerization for octane improvement and feed Stream B to
 321 the coker fractionator for conversion/upgrading via hydrocracking and
 322 cat cracking. (The diesel fraction was found to be too low in cetane to
 323 consider direct blending into product.) An initial cost estimate for this
 324 approach indicates the refining costs would increase only by about
 325 11% vs. the base case of upgrading to 0.2% oxygen. The key assumptions
 326 in estimating the refining costs were that the oxygen was removed as
 327 water and the remaining hydrocarbon content behaved as would simi-
 328 lar hydrocarbons in conventional refining. It should be emphasized that
 329 this estimated cost of refining does not include any unusual costs (cor-
 330 rosion protection, process yield and operating cost debits, etc.) to pro-
 331 cess these potential bio-crudes. These assumptions would, obviously,
 332 have to be confirmed with pilot plant testing. Given that this calculation
 333 represents an optimistic refining cost estimate, the economics were also
 334 tested with refining costs for handling the partial upgrading Pyoil that
 335 are double the base refining costs.

336 Using these various assumptions the incentives for partial upgrading
 337 are shown in Table 1.

338 As can be seen the incentive for partial upgrading could be sub-
 339 stantial, but is highly uncertain depending on yield and refining cost
 340 assumptions. The incentive is highly sensitive to upgrader yield, where-
 341 as refining costs have significantly less impact (refining cost are only
 342 about 7% of the value chain costs in the base case). These incentives
 343 are primarily due to the improved yield of products out of the partial
 344 upgrading/refinery combination vs. the base case of upgrading oxygen
 345 extinction before refining. The refinery processes appear to be better
 346 able to preserve valuable hydrocarbons than does the single high pres-
 347 sure upgrader.

^c An alternative option for treating Stream A might be direct product blending vs. octane upgrading via reforming/isomerization. Stream A was found to need some additional octane improvement when upgraded all the way to 0.4% oxygen. It is not known if upgrading to an oxygen level above or below 0.4% will yield a stream with high enough octane for direct product blending. Another significant unknown is how much Pyoil oxygen can be tolerated in the product. Blending off high oxygen content Pyoil into finished product might be more economic than trying to treat it to oxygen extinction. Direct blending into product would have the advantage of avoiding any processing difficulties and costs associated with reforming/isomerizing this stream. This option would obviously require careful product quality testing before consideration.

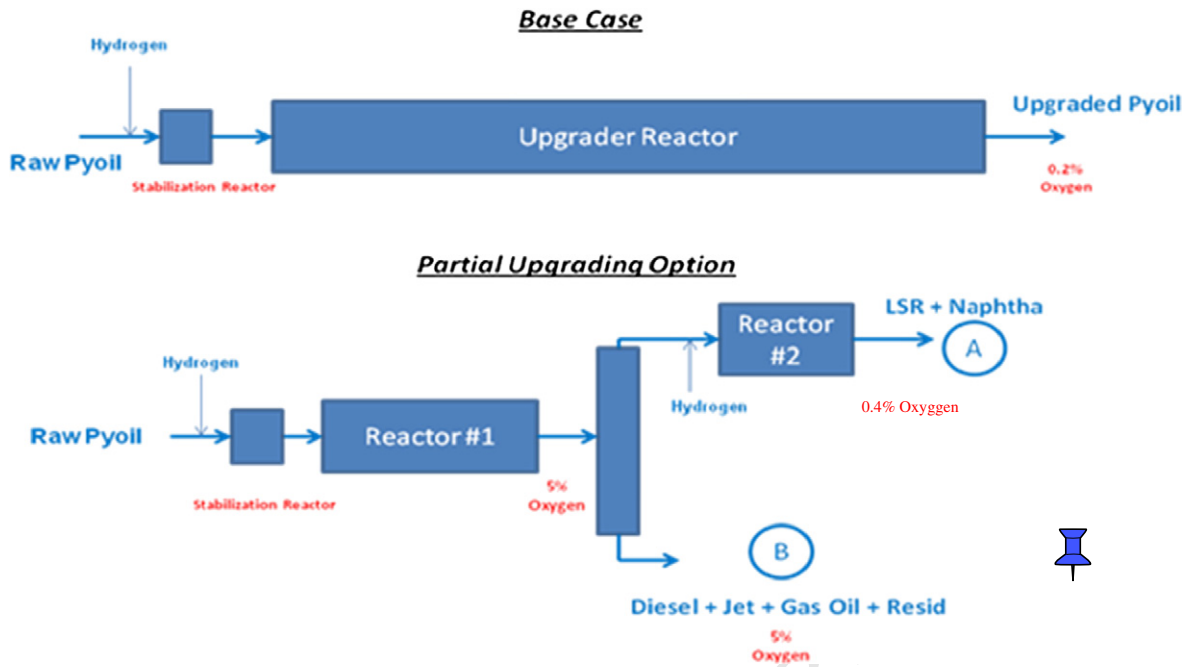


Fig. 5. Partial upgrading option.

Even if the analytical results reported above are not duplicated, the discussion above illustrates the kinds of opportunities that are largely unexplored at the upgrader/refinery interface. To progress the area of partial upgrading, the key is more fully defining the properties of partially deoxygenated Pyoil as a function of boiling point/upgrading severity, and determining what the maximum level of Pyoil oxygen refineries can safely handle. Some of the first areas to examine, in addition to the obvious ones of corrosion and heat exchanger fouling, include (1) defining the feasibility of direct blending of partially upgraded LSR and naphtha streams into gasoline (can some level of upgrading produce material with high enough octane to avoid catalytic processing?), (2) establishing how much of the partially upgraded Pyoil oxygen species can be tolerated in gasoline and diesel (can blending into product be used instead of extra upgrading to get rid of oxygen?) and (3) defining the need to hydrotreat partially upgraded Pyoil prior to cat cracking (where can hydrotreating in the refinery be avoided?).

Broadly, what one is looking for are strategies that use blending as an alternative to catalytic processing and that minimize processing that requires use of expensive hydrogen. Depending on what is found as the limiting factor, potential additional areas to study include oxygen tolerant refinery catalysts, improved corrosion management of Pyoil specific acids and fuel additives to offset any product quality issues found. These overall research areas are largely unexplored.

4.2.2. Oxygen removal at pyrolysis step

The overall motivation for removing some of the oxygen in the pyrolysis step is premised on the idea that this can be done more cost effectively than accomplishing all removal at the upgrader. More specifically, pyrolysis stage oxygen removal could realize a twofold cost

saving; (1) reducing the net upgrading costs by removing oxygen as carbon oxides vs. using expensive hydrogen and reducing the upgrader size/investment and (2) producing a Pyoil product that is more stable, making it easier to move logistically and for the upgrader to handle.

The base process produces a raw Pyoil containing 30–40% oxygen. It is known that extensive modification of pyrolysis, as represented by the liquefaction process, does, in fact, produce a product with significantly lower oxygen content (12–14%) [7] and is more stable and easier to handle in the upgrading step [6]. Unfortunately, the cost of the liquefaction process largely offsets the benefits of a less costly upgrading step [8]. If modifications could be found that are significantly less costly than liquefaction, they would be of interest. Shell's HTU process attempts to simplify and reduce the cost of this process by eliminating the catalyst and carbon monoxide [9]. A more recent effort is Gas Technology Institute's H₂-2 process [10] (combined hydropyrolysis and hydroconversion process), where its hydropyrolysis product is reported to be ~2% oxygen. RTI International, in collaboration with ADM, ConocoPhillips and Albemarle, recently received an ARPA-E contract to develop a "single-step catalytic biomass pyrolysis process with high carbon conversion efficiency to produce stable bio-crude with low oxygen content (<10%)" [11]. KiOR, a Houston based company, is pursuing another approach [12]. They are looking at a catalytic fluid bed process to convert the biomass and remove oxygen. Product oxygen from this process has not been reported. They are currently constructing a 500 t/d plant in Columbus, MS.

Possibilities that could be explored in this area might include changes in the operating conditions in the pyrolysis unit including the use of catalysts, hydrogen donors or hydrogen as well as various feed pretreatment and product post treatment steps to reduce the oxygen content of the raw Pyoil without sacrificing hydrocarbon yield. One could even consider genetically modified trees tailored to the pyrolysis step. A lack of understanding of the impact of feedstock properties on Pyoil oxygen significantly limits opportunities in this area however.

In setting a research target for pyrolysis oxygen removal, a Pyoil level of 10 wt.% oxygen (dry basis) was chosen based on the performance of

^d In the liquefaction process wood is slurried with water, recycle oil product and a sodium carbonate catalyst at high temperature (350 °C) and pressure (20.8 Mpa) with carbon monoxide.

Table 1
Incentives for partial upgrading.

Assumed upgrader yield	Assumed refining	Cost incentive
Optimistic (69%)	Optimistic (+11%)	17%
Pessimistic (57%)	Optimistic (+11%)	9%
Optimistic (69%)	Pessimistic (2× Base)	11%
Pessimistic (57%)	Pessimistic (2× Base)	3%

the liquefaction process which could be considered a surrogate for a modified pyrolysis process. Higher target levels of oxygen could be considered, but are believed to have separation and handling problems because of (1) similar density of Pyoil and water, (2) increased viscosity of the Pyoil and (3) the potential for significant dissolved hydrocarbon loss in the waste water [6]. If one selects this as a target for modifying the pyrolysis process, the potential reduction in the value chain costs is estimated to be 7–9%. The actual savings achieved would be offset by any incremental cost in the pyrolysis step required to accomplish this target. Again the challenge is to affect oxygen removal in the pyrolysis step at low cost. The additional (and possibly more important) benefit of oxygen removal at the pyrolysis step is that the reported severe catalyst fouling/deactivation in the upgrading step might be significantly reduced. There is clear evidence that the product from the liquefaction process mentioned above displays reduced upgrader catalyst fouling and deactivation [13].

4.3. Yield improvement incentives

The yield from both the pyrolysis and upgrading steps has a significant effect on the economics. For the n -th plant analysis done by PNNL [13], the yields used assumed significant progress in yield from now until the n -th plant was built; such assumptions are typical and not unreasonable for this kind of study (in their study they assumed the pyrolysis yield was 0.65 lbs raw, dry Pyoil / lbs dry wood and 0.55 lbs upgraded Pyoil/lbs. of raw dry Pyoil.). In terms of the pyrolysis step, current literature values vary widely [14], especially if residues (bark, foliage) are included. The value used for the n -th plant is at the very upper end of literature values and is for heartwood. Residues and bark/thinnings give lower yields (51% and 53% vs. 60% from heartwood) which seem to correlate with lower volatiles and higher ash content. Some researchers have shown acid treating of wood to remove ash from wood does, in fact, improve pyrolysis yields [15]. Recent studies directly comparing pyrolysis of heartwood vs. whole trees have shown yields for whole trees to be 6% to 9% lower than for heartwood [16]. A more realistic estimate of current technology pyrolysis yield, therefore, would be about 58%. The reported yields above are from very small laboratory studies. It is not known how well these small scale yields survive the scale up to commercial sized pyrolysis reactors, given the sensitivity of bio-oil yields to vapor phase residence time and temperature. This further argues for using a lower yield to represent current technology vs. the PNNL basis above.

In terms of upgrading yields there is limited recent information available. Early data from VEBA [4] reported yields of ~45 wt.% (upgraded Pyoil/raw, dry Pyoil). More recent information [17] measured yields in the 48–54% range. Again the data are from small scale laboratory units. For this paper the base case upgrader yield selected was 50%.

Table 2 quantifies the impact of increasing pyrolysis and upgrading yields on value chain costs.

Note that these calculations assume that the product oxygen from each process step remains the same as the yields are improved. Yields from both the upgrader and pyrolysis units are important as the overall yield improvements are the arithmetic product of the yields from each step. The value chain cost reduction for yield improvements in both steps is about 13%. In the pyrolysis step, potential yield improvement areas might include exploring feed pretreatment to remove ash or to add a catalyst. In the upgrader, finding a catalyst that shows

Table 2
Impact of pyrolysis and upgrader yields on value chain costs.

Process step	Base yield	Potential future yield	Value chain cost reduction
Pyrolysis	58%	65%	6%
Upgrading	50%	55%	6–7%

lower cracking to light ends might represent an opportunity area. The key issue is the cost of achieving these improvements.

4.4. Biomass research

The costs of producing, harvesting, chipping and shipping the biomass component account for up to 48% of the total fuel cost plus return in our models, depending mostly on location, and provide a substantial opportunity for research and development leading to cost reduction. Increasing the dry biomass yield per acre/year has the greatest impact on the total quantity of fuel products that can be sustainably produced using the technology. Higher yields allow more concentrated production and collection, which would reduce shipping costs. To the extent that yields are high enough to support large scale pyrolysis operations located close to the biomass resource, savings as high as 9% of total value chain costs could be obtained without losing the economies of scale of centralized pyrolysis. Reduction in plantation and harvesting/chipping costs by 25%, influenced in part by more concentrated biomass production, could reduce the value chain cost by 5% and 4%, respectively.

Longer term potential lies in modifying biomass composition to better suit the pyrolysis and upgrading processes. Materials that would require less preparation produce Pyoil with less oxygen, lower water content, and/or lower trace element content would provide cost and operational benefits. Specific programs and objectives in this area were beyond the scope of our study.

5. Conclusions

A competitive pyrolysis value chain will require a combination of significant technical advances from the current state of the technology. The two largest technical uncertainties affecting the value chain's viability are (1) upgrader catalyst life and (2) the allowable level of Pyoil oxygen the existing refinery infrastructure can handle. Once these are defined, optimization of oxygen removal in the value chain both upstream and downstream of the upgrader, and plantation/upgrader/pyrolysis yields appear to have the greatest impact on the overall economics. These represent the research areas with the highest potential for cost reduction. The ultimate challenge is to make progress in these areas while not eroding the projected savings.

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