Independent Assessment of Technology Characterizations to Support the Biomass Program Annual State-of-Technology Assessments

April 2010 – October 2010

Bryan Yeh
Science Applications International Corporation
Oakland, California

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Subcontract Report
NREL/SR-6A10-50441
March 2011

Contract No. DE-AC36-08GO28308

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

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NREL Technical Monitor: Mark Ruth
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National Renewable Energy Laboratory
1617 Cole Boulevard
Golden, Colorado 80401
303-275-3000 • www.nrel.gov

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Executive Summary

Understanding the state of technology for innovative technologies is critical in determining the opportunities for improvement, how one technology compares with another, and what resources are necessary for commercialization. This investigation addressed two thermochemical conversion pathways for the production of liquid fuels as well as the steps to the process, the technology providers, a method for determining the state of technology, and a tool to continuously assess the state of technology.

The investigation revealed the difficulty in obtaining information that can yield a comprehensive assessment and the bias that potentially occurs when information is not available. When information was available, there was further difficulty in verifying that the method by which the data was generated was consistent from vendor to vendor. This report summarizes the findings of the investigation as well as provides recommendations for improvements for future studies.

Acronyms and Abbreviations

BFB	bubbling fluidized bed
BTG	Biomass Technology Group
BTL	biomass to liquids
CFB	circulating fluidized bed
CO	carbon monoxide
CO_2	carbon dioxide
CUTEC	Clausthaler Umwelttchnik-Institut
DOE	U.S. Department of Energy
EFB	empty fruit bunch
FT	Fischer-Tropsch
GHG	greenhouse gas
GTI	Gas Technology Institute
H_2	hydrogen
MT	metric ton
MW	megawatt
OBP	Office of Biomass Programs
PDU	Process Development Unit
REII	Renewable Energy Institute International
SAIC	Science Applications International Corporation
SOT	state of technology
SWRC	short-rotation woody crop
TPD	tons per day
TRI	ThermoChem Recovery International
TRL	technology readiness level
TUV	Technical University of Vienna

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1 Introduction

The goal of this project is to better define, track, and communicate the status and progress of cellulosic biofuel production processes. The key project objectives are to: (1) establish a transparent, straightforward, and non-proprietary approach to assess and synthesize process and economic data from U.S. Department of Energy (DOE) industrial-led projects at a range of scales—as the basis for generating consistent and comparable annual state of technology (SOT) metrics for specified feedstock-conversion-biofuel combinations; (2) document the current SOT of specified feedstock-conversion-biofuel combinations; (3) establish future SOT targets for each feedstock-conversion-biofuel combination; and (4) build on this framework to quickly and consistently assess and compare new concepts and technologies.

The multitude of possible biomass feedstocks, conversion process configurations, and biofuel options is captured in the DOE's Office of Biomass Program (OBP) biorefinery pathway framework. Each pathway is linked to a portion of the U.S. biomass resource base identified in the "Billion Ton" study and a processing configuration that either exists within the current bio-industry or is envisioned in a future market. Appendix A of the 2007–2017 DOE OBP Multi-Year Plan[1] provides detailed flow diagrams and prioritized technical milestones for each pathway.

Two of OBP's core processes were evaluated in this project, which are based on a specific feedstock-conversion-biofuel combination, or route, through a specific pathway.

Table 1. Core Conversion Processes Aligned With Pathway Routes

Core Process	Feedstock	Conversion Configuration	Biofuel	OBP Pathway-Route
#4	Forest wood residue	Thermochemical (gasification + Fischer-Tropsch synthesis)	Renewable gasoline/diesel (as blending products)	Forest resources (6.1, 6.2, 6.11, 6.13)
#5	Hybrid poplar	Thermochemical (pyrolysis/liquefaction + hydrocracking/treating)	Renewable gasoline/diesel (as blending products)	Energy crops (5.2, 5.19, 5.20)

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[1] DOE Biomass Program Multi-Year Plan 2010: www1.eere.energy.gov/biomass/pdfs/mypp.pdf.

2 Methodology of Data Collection

The first step that the Science Applications International Corporation (SAIC) team undertook in this project was to determine the different entities that are participating in the identified core processes. These entities include technology providers, universities, start-up and Fortune 500 companies, and research labs. For each entity identified, we:

1. Sought permission to obtain data that resulted from DOE's funding opportunity announcement DE-PS36-09GO09938 or earlier funding opportunities. Most of the information necessary to perform this project could be found on two Excel spreadsheets named TechandFinData.xls and Proforma.xls, respectively, as well as the Word file PFD_Data.doc. Unfortunately, we were not able to obtain permission to use these data.
2. Assessed information in our database. SAIC has a library of presentations that have been made over the past two years that are categorized by the different technology groups and entities. This information was used as part of the data gathering process.
3. Conducted an extensive literature search to determine what information exists in published data. This search included presentations that have been made in conferences such as the annual meeting of the American Institute of Chemical Engineers, the American Chemical Society, and the International Energy Agency, as well as annual reports and patent literature.
4. Contacted the different entities directly to obtain missing information and to clarify information on third-party reports.

Additionally, ground rules for obtaining data were established to ensure consistency, accuracy, and appropriate disclosure. These included:

- The process steps as defined in Table 1 were used as the basis for investigation. For example:
    - Information regarding the pyrolysis of soybeans was not considered in this project as it was deemed "not similar" to the pyrolysis of hybrid poplar.
    - Information regarding the pyrolysis of pine was considered in this project as it was deemed "similar" to the pyrolysis of hybrid poplar.
    - Gasification systems that produced synthesis gas for purposes other than Fischer-Tropsch (FT) synthesis were not considered as they have different requirements and objectives from what is intended for Core Process #4 as defined above.
    - Gasification systems that were originally developed for purposes other than FT synthesis but were now being considered for FT synthesis were considered as long as there was a paper study that supported its use.
- Processes that deviated slightly from what was defined above were considered in this study as long as they demonstrated a significant benefit that might advance the development of the overall technology. The specific cases where this was done include:

    - Catalytic pyrolysis
    - Vacuum pyrolysis
- Only data that were obtained without the need for a nondisclosure agreement were used in this project.
- Under no circumstances would information that is considered confidential be used in this project.

We found that in many recent publications old information was being recycled. This was a result of available funding that occurred in cycles, hence leaving gaps in time where no significant work was performed. Due to stimulus funding as well as a concern for fluctuating oil prices and supply, significant work in the different pathways has commenced since 2008, resulting in a large number of publications, patents, and news releases being produced in the past few months. For this project, the team has incorporated most of the information that is currently available; however, the field of interest remains very dynamic.

3 Process Descriptions

3.1 Gasification Pathway (Core Process #4)

The gasification pathway (Core Process # 4) is shown in Figure 1. For this project, it was assumed that forest residue would feed the process. Forest residue comes from one of two sources; either it is the residual wood consisting of tree tops and small branches that are left behind as a result of logging operations, or it consists of undergrowth in forests that are harvested to reduce the risk of forest fires.[2] These are shown as blocks 6.1 and 6.2, respectively.

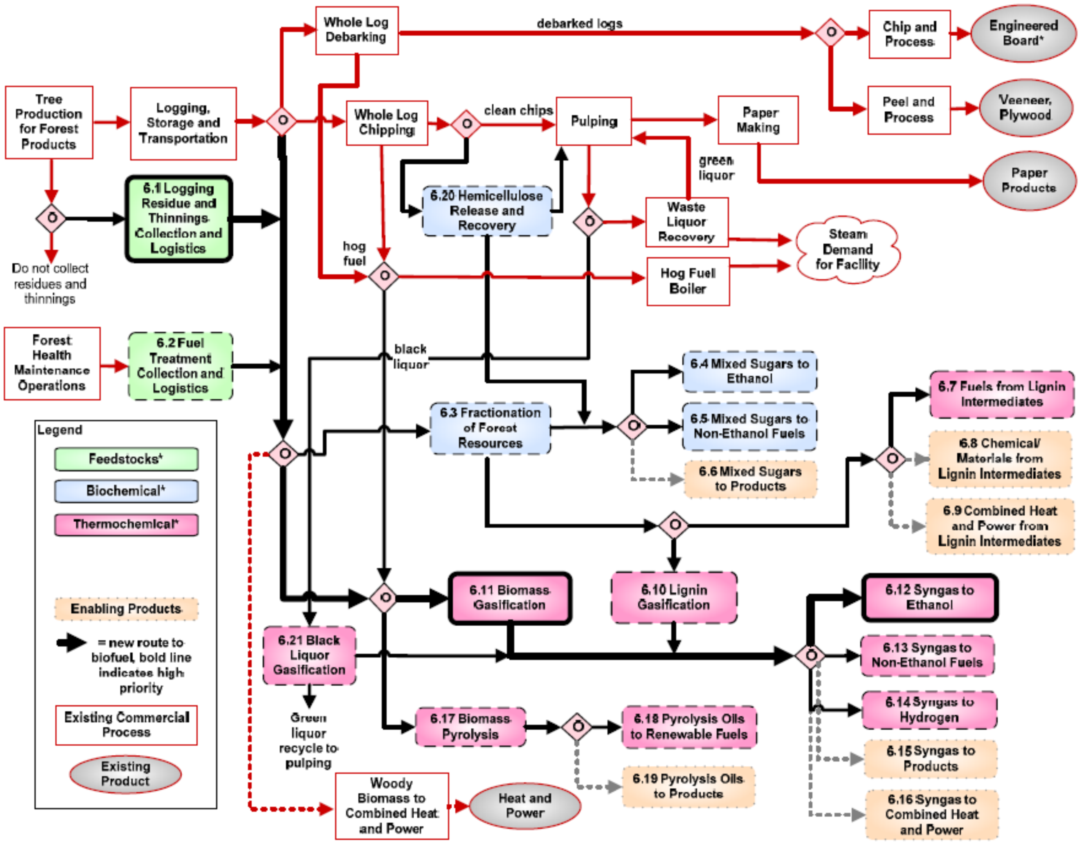

Figure 1. Gasification pathway (Core Process #4)[3]

Forest residue is then sent to biomass gasification for conversion to synthesis gas. Gasification is a process that uses high temperature and a controlled amount of oxygen to break down organic materials into a gaseous product known as synthesis gas. Synthesis gas consists primarily of hydrogen (H_2) and carbon monoxide (CO), with traces of carbon dioxide (CO_2), methane, tar, and ash. This process is shown as block 6.11.

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[2] R.D. Perlack et al, "Biomass as a feedstock for a Bioenergy and Bioproducts industry: The Technical Feasibility of a Billion-Ton Annual Supply," April 2005

[3] DOE Biomass Program Multi-Year Plan 2010: www1.eere.energy.gov/biomass/pdfs/mypp.pdf

The H_2 and CO in synthesis gas form the building blocks that are used to make straight chain alkanes in a reaction known as the *Fischer-Tropsch) synthesis*, which has been commercialized in South Africa and several other countries for the production of liquid fuels from carbon sources such as coal and natural gas. This process is shown as block 6.13.

3.2 Pyrolysis Pathway (Core Process #5)

The pyrolysis pathway (Core Process #5) is shown below in Figure 2. For this project, it was assumed that hybrid poplar, a fast growing tree that is used for short-rotation woody crops (SRWCs), would be used as the feedstock. This is shown as block 5.2.

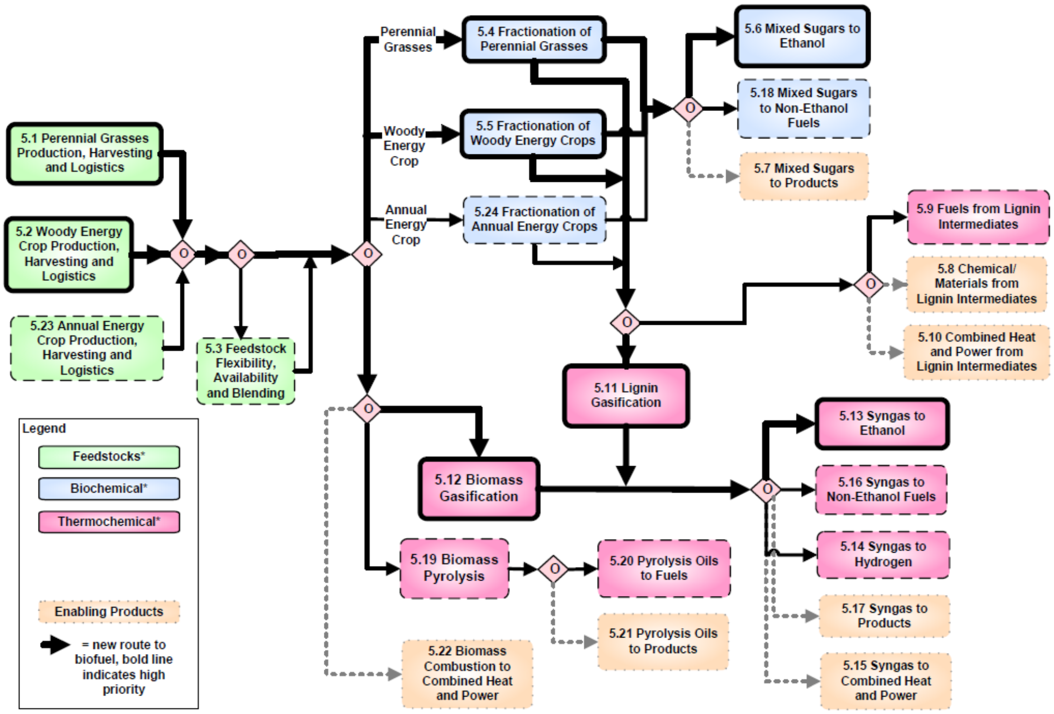

Figure 2. Pyrolysis pathway (Core Process #5)[4]

Pyrolysis is a process that utilizes high temperature (around 500°C) in the absence of oxygen to decompose organic materials.[5] The rate at which heat transfer takes place dictates the amount of char or pyrolysis oil that is produced. When the heat transfer rate is fast, or at least 550°C per second,[6] the production of pyrolysis oil, or bio-oil, is favored.[7] This process is known as fast pyrolysis and is the process depicted in block 5.19 above. For this project, catalytic and vacuum pyrolyses were also considered and are variations on classical fast pyrolysis.

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[4] DOE Biomass Program Multi-Year Plan 2010: www1.eere.energy.gov/biomass/pdfs/mypp.pdf

[5] Tony Bridgewater, "Fast pyrolysis based biorefineries," American Chemical Society Annual Meeting, Washington, D.C., August 31, 2005

[6] Badger, P.C., "An Overview of Fast Pyrolysis," Georgia Bioenergy Conference, Tifton, GA August 1–3, 2006

[7] M. Ringer, V. Putsche, J. Scahill, *Large-Scale Pyrolysis Oil Production : A Technology Assessment and Economic Analysis*, NREL/TP-510-37779

There are several parameters that are critical when carrying out fast pyrolysis:[8]

- Feed material should be dried to below 10% moisture.
- With the exception of an ablative or vacuum reactor, particle sizes should be no greater than 3 mm.
- Biomass must be heated as quickly as possible.
- Control of reaction temperature is critical.
- Vapors should be cooled as quickly as possible.
- Minimize contact between vapor and char/ash.

Pyrolysis oil from fast pyrolysis has numerous properties that make it unsuitable for widespread use as liquid fuels. These properties include low pH, high water content, low heat value, and chemical instability.[9] Further upgrading is required to produce a product that can be incorporated into current petroleum infrastructure. In Figure 2, this process is shown as block 5.20.

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[8] Tony Bridgewater, "Fast pyrolysis based biorefineries," American Chemical Society Annual Meeting, Washington, D.C., August 31, 2005

[9] Elliott, D.C., et al. "Catalytic Hydroprocessing of Biomass Fast Pyrolysis Bio-Oil to Produce Hydrocarbon Products," *Environmental Progress & Sustainable Energy* 28:3, 441–449

4 Task Descriptions

The work for this project was separated into two tasks:

Task 1, titled, "Data Collection and Documentation," required the SAIC team to collect and evaluate process and economic data that are relevant to the gasification and pyrolysis pathways. Furthermore, the team was expected to determine the potential for future cost reductions.

Task 2, titled, "SOT Data Requirements and Reporting Framework," required the SAIC team to synthesize a common set of technical, economic, and data quality metrics to define the state of technology for each of the specified pathways. This task was further broken down into four subtasks:

Subtask 2.1, titled, "Define Required SOT Data," is divided into three separate parts:

> ***Part 2.1.1*** requires that the pathways be broken down into a simplified block flow diagram and that for each block within the diagram, key performance and operating metrics are selected to help evaluate the state of technology.
>
> ***Part 2.1.2*** requires that key economic metrics be defined for each block when evaluating the state of technology.
>
> ***Part 2.1.3*** requires that a set of overarching economic and technical metrics be defined that would allow comparison across different pathway routes.

Subtask 2.2, titled, "Establish Data Quality Metrics Assessment Methodology," requires the team to establish a standardized framework and methodology to document, assess, and track the quality of data collected. As a point of reference, a publication titled, "Technology Readiness Assessment/Technology Maturation Plan Process Guide," for the DOE, Office of Environmental Management, March 2008, was used as a basis for establishing data quality.

Subtask 2.3, titled, "Establish Framework for SOT Reporting/Tracking," requires the team to develop an easy-to-update desktop tool that will facilitate the tracking and communication of the state of technology of the different pathways.

Subtask 2.4, titled, "Synthesize/Normalize Collected Process Data," requires that the team utilize the tool from subtask 2.3 to synthesize all of the data collected and to present the findings.

5 Task 1 Results

5.1 Gasification Pathway

5.1.1 Forest Residue

Forest residue is defined as coming from one of two primary sources:

- The residue that is associated with the commercial harvesting of wood for the purposes of producing sawlogs, pulpwood, veneer logs, and other wood products
- The non-merchantable biomass that is removed from forests, such as rough and rotten wood and small diameter trees that are removed to improve forest health and to reduce the risk of wildfires.

According to a 2005 study performed by Perlack et al.,[10] up to 41 million dry tons of logging residue and 60 million dry tons of forest thinnings are available annually. However, today, it is estimated that approximately 10% of the available residue is recovered and the remaining material is burned on site.[11] Much of this is driven strictly by economics. The cost of recovery varies greatly, and is very much a function of the terrain, road access, logging practice, and the distance to the user. For example, it was determined that when harvesting thinnings on slopes less than 35%, revenues of $950 per acre were possible, however, slopes steeper than 35% will require a subsidy of over $300 per acre to break even.[12] Baseline harvesting costs are $260-$360 per acre.[13]

Logging practices have a great effect on the economics of recovering forest residue. For example, in most operations in North America, the forest thinnings and logging residues are placed into slash piles. Since these slash piles are arranged for burning and not for processing, it takes twice the amount of effort to collect and process the residue than it would have if the slash piles were stacked and not pushed.[14]

An alternative practice, called cut-to-length harvesting, has been commercialized in Scandinavia. The cut-to-length” method involves processing the felled trees into defined log lengths at the stump, hence creating a more organized system for separating and collecting the products and co-products. Equipment, such as a slash bundler, is then used to collect the woody residue on the ground and produce a compacted bundle that can be loaded onto a flat bed truck for further processing.[15]

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[10] Perlack et al., “Biomass as Feedstock for a Bioenergy and Bioproducts Industry: The Technical Feasibility of a Billion-Ton Annual Supply,” DOE/GO-102005-2135 (2005)

[11] Bradley, D. 2006) *Canada Biomass-Bioenergy Report*, Climate Change Solutions /www.climatechangesolutions.net/pdf/canada_country2006.pdf

[12] Fiedler, C.E., et al., Product and economic implications of ecological restoration. *Forest Products Journal* (1999) 49(2): 19–23

[13] Leinonen, A., “Harvesting technology of forest residues for fuel in the USA and Finland,” VTT Research Notes 2229

[14] Forest Biomass Removal on National Forest Lands, First Progress Report, November 17, 2008, Sierra Nevada Conservancy

[15] Forest Residues Bundling Project – New Technology for Residue Removal, May 2004, Forest Operations Research Unit, Southern Research Station, Auburn, Alabama

Although there are no commercial examples of the use of forest residues for the production of biofuels using gasification, there are numerous power-generating plants in North America that use forest residue. In California alone, it is estimated that 6.4 million dry tons per year of biomass is consumed by 29 power plants, of which 2–3 million tons per year is estimated to be forest residue.[16] One is the Wheelabrator Shasta Energy power plant in Anderson, California. This plant generates 58 megawatts (MW) of power and processes 750,000 dry tons of biomass per year, of which approximately 150,000 dry tons is forest residue, which includes non-merchantable waste wood from Shasta-Trinity and Lassen National Forests, as well as private land.[17]

Power companies such as Wheelabrator, Covanta, Boralex, and Marubeni do not harvest the forest residue. Most of these companies buy the forest residue on the spot market from anywhere between 50-150 private enterprises per site. The source usually does not exceed beyond a 70 mile radius from the plant. The forest residue is usually collected from a slash pile at a landing site. A common method is to collect the slash using Link-Belt excavators and grinding the slash using a Bandit Beast horizontal grinder. The processed slash is conveyed directly from the grinder to a chip van where it is directly transported to the facility. In a study by the Sierra Nevada Conservancy, it was found that some practices were critical in keeping costs low:[18]

- Piles should be on flat ground, be less than two years old, and stacked neatly.
- Piles should not be pushed together with a bulldozer as this will add dirt to the fuel and impact its quality.
- Piles should fill no less than 10 truckloads.
- Trucks should be scheduled to keep the grinding equipment running continuously.

To properly depict the state of technology for forest residue, the team decided to focus on the end user as opposed to trying to focus on the individual contractors who harvest and sell the forest residue. The rationale for this is that the methods and equipment used by the different contractors vary tremendously. By showing where the users were demonstrates the maturity of the utilization of forest residue.

5.1.1.1 Wheelabrator Shasta Energy Company

This plant is in Anderson, California, and runs on woody biomass. Wheelabrator operates 22 power plants, most of which function on municipal solid waste. The Polk County, Florida, plant utilizes 300,000 tons of waste wood per year, although it is unclear if any of this is forest residue.

5.1.1.2 Marubeni Sustainable Energy

Marubeni is best known as one of the largest trading companies in Japan. It currently operates three plants that utilize about 750,000 tons of forest residue per year. Its plants are located in

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[16] Leinonen, A., “Harvesting technology of forest residues for fuel in the USA and Finland,” VTT Research Notes 2229

[17] www.wheelabratortechnologies.com/wtius/index.cfm/our-clean-energy-plants/independent-power-plants/wheelabrator-shasta-energy-co-inc/

[18] Forest Biomass Removal on National Forest Lands, First Progress Report, November 17, 2008, Sierra Nevada Conservancy

Samoa, California; Whitefield, New Hampshire; and Springfield, New Hampshire. The plants purchase forest residue on a spot basis from 50–150 suppliers.

5.1.1.3 Boralex

This is a Québec-based developer and operator of independent power projects. Its facilities are located in Canada, the United States, and France. The firm was created in 1982 as a joint venture between the leaders of Laduboro, Albany Oil, and Exar. In total, Boralex uses about 725,000 tons of forest residue annually and operates six wood-fired power plants in Chateaugay, New York, and Maine, including Ashland, Fort Fairfield, Livermore Falls, Stacyville, and Stratton.

5.1.2 Gasification and Fischer-Tropsch Synthesis

Core Process #4 consists of gasification of forest wood residue as the conversion technology, followed by FT synthesis as the upgrade technology to produce green diesel or gasoline. Gasification is a thermochemical partial oxidation process in which solid organic carbon feed (in this case, biomass) is broken down into gaseous components that can be utilized as a fuel. While gasification technology is not new, its application to biomass feed is. Unlike combustion, where organic carbon is fully oxidized to CO_2 and water, gasification utilizes a sub-stoichiometric quantity of oxygen to convert the feed to CO and H_2, referred to as synthesis gas or syngas. Other typical products of gasification include higher molecular weight carbon species, or tar, and residual solid carbon, or char. Typical oxidants are either air, oxygen, or steam. Gasification is an endothermic reaction. The necessary heat is either supplied by burning some of the solid feed material in a separate zone within the gasifier, or by supplying heat indirectly from an external source. Gasification is often carried out in more than one step characterized by different quantities of oxidant and different operating conditions. The particular gasifier design, heating method, oxidant used, and number of steps are often what distinguish one vendor's design from another. The syngas produced from a gasifier has significant heating value and can be either burned as a clean fuel for heat and power or, as is the interest here, can be used as the building blocks for generating high molecular weight liquid fuels.

There are many types of gasifier designs in use. While the most traditional design is the fixed bed, this is not popular among vendors specializing in biomass gasification. Instead, the most common gasifier types for biomass are the fluidized bed or entrained flow designs. Variations of the fluidized bed design include the bubbling fluidized bed (BFB), circulating fluidized bed (CFB), and dual fluidized bed, which consist of separate fluidized bed chambers for gasification and combustion. The gasifier type utilized by each technology provider surveyed in this study is included in Table 2.

Table 2. Gasifier/FT Technology Designs

Technology Provider	Gasifier Type	FT Reactor Type
Choren	Entrained flow (3 stage)	Fixed bed
Clearfuels/Rentech	Entrained flow	Slurry bubble column
CUTEC	CFB	Fixed bed
GTI/UPM-Kymmene/Carbona	BFB	Not designed yet
Red Lion Bio-energy/Pacific Renewable Fuels/REII	BFB (2 stage)	Unspecified catalytic reactor
RTI	Dual fluidized bed	Not designed yet
Stora Enso/Neste Oil/VTT	CFB	Unspecified catalytic reactor for current tests; commercial design not yet chosen

Technology Provider	Gasifier Type	FT Reactor Type
TRI	BFB (2 stage)	Fixed bed
TUV	Dual fluidized bed	Tubular slurry reactor
Velocys	Dual fluidized bed	Microchannel reactor

As with gasification, FT technology was established long before the relatively recent interest in biomass conversion. It was developed in the early 20th century to convert synthesis gas to hydrocarbons, and pursued primarily in areas with limited access to traditional petroleum sources such as Germany during World War II and South Africa during the years of Apartheid. The FT process involves a polymerization reaction that creates chains of hydrocarbons utilizing a heterogeneous catalyst and is exothermic. It takes place at moderately high temperatures (e.g., 200°–350°C) and pressures (e.g., 20–60 bar). The type of catalyst is usually either cobalt or iron based. In general, cobalt has a higher conversion rate and is more durable but more expensive than iron. Iron has a higher tolerance for impurities in syngas, is more active for the water gas shift reaction, and is less expensive than cobalt, but has a shorter lifetime. Traditional FT reactors are large, and of either the multitubular fixed bed or slurry bubble column type. However, there are smaller, new designs being developed, such as the microchannel reactor of Velocys. Most FT processes require a certain CO/H_2 ratio in the syngas feed and a maximum tolerance for impurities, which usually results in the need for an upstream gas cleanup system when integrated with a syngas generation technology such as gasification.

There are a number of vendors or technology providers surveyed for this assessment study that have a process consistent with part or all of core process #4. To be included in this report, a vendor had to meet the following criteria as dictated by Core Process #4:

- Must have an integrated gasification/FT process. The complete system does not have to be operational but there must be at least a design, or intent to design, a fully integrated system (this eliminates the many vendors and projects focused solely on gasification for heat and power only).
- Must have demonstrated operation with woody biomass or have a design that is intended to operate on woody biomass. While operation specifically with forest residue is the preferred scenario, any form of woody biomass, for example, wood chips, was considered acceptable to assess technical performance of the integrated system. Although coal gasification is well developed, the team did not consider any vendors that only had coal gasification experience as coal gasification has distinctly different feed characteristics and typically operates at a different scale due to the energy density of the feedstock.
- Must produce, or intend to produce, liquid diesel or gasoline fuel generated via the FT process. This eliminates vendors focused on alcohol or gasoline production via the methanol and/or dimethyl ether process.

There was no requirement placed on vendors having achieved a minimum scale size. Also, there was no restriction on vendor type, and those surveyed ranged from commercial companies to more research-oriented organizations and universities. Ten vendors meet the above criteria and are included in this evaluation. An overview of each vendor's process is provided below. In most, the FT product is a synthetic crude that requires further refining before achieving petroleum-quality diesel fuel.

Few biomass-fed gasifier/FT-integrated systems are in operation; however, at least nine large-scale systems are expected to become operational within the next few years. Thus, this technology status is in a state of flux with a period of rapid change expected in the near future. The long-term maturity and viability of biomass gasification/FT can be much more accurately assessed once these projected plants become operational in the next few years.

On the question of greenhouse gas (GHG) reduction, several of the technology providers were able to provide their GHG reduction estimate as compared to petroleum. In all cases, this did not include CO_2 recovery.

The main areas for improvement for all gasification/FT technologies are related to scale-up and cost. Most technologies can work at a small scale, but operation at a size necessary for commercial production has not yet been achieved. Likewise, the costs of producing the relatively small amounts of FT product in existing small-scale systems makes the per gallon cost much too expensive to be competitive at the present time. The gas cleanup section of the process and the FT catalyst are two components that have a significant impact on the overall cost, and are areas where improvements can have a big effect. Gas cleanup consists of several steps to prepare the syngas to meet the downstream FT catalyst requirements. Methods that can help minimize the number of steps, improve efficiency, or recover and reuse sensible heat from the hot syngas can positively affect cost. The FT catalyst type used by most vendors is either iron- or cobalt-based, although research on combinations and mixtures with other components is ongoing. An improved catalyst design that can result in faster kinetics will also result in a more efficient and cost-effective process.

5.1.2.1 Choren

Choren is a German company specializing in gasification technology. It has developed the three-step Carbo-V process that involves an initial low-temperature gasification without oxidant followed by a high-temperature gasification with oxygen. Tar produced from the low temperature gasifier is burned to provide heat in the high temperature gasifier. Choren holds a license from Shell for the FT technology, which is based on a multi-tubular fixed-bed reactor design. However, as of early 2010, Shell is no longer a partner with Choren. Thus, future plants (after the Freiberg Beta plant) will likely employ a different FT technology.

Choren built a pilot plant, Alpha, in 2003 which accumulated about 17,000 hours of operation but is no longer running. Their Beta plant in Freiberg, Germany, is essentially a commercial-scale plant that was built in 2008. The plant is mechanically integrated but has been started in stages to ensure reliable operation. The gasifier began operating in November 2009 and has been running intermittently since then as it goes through start-up (about 600 hours of operation to date). As of June 2010, the FT portion has not yet begun as Choren wants to ensure steady and stable gasifier operation before running the two systems together. Choren has utilized a feed of low grade wood in the Beta plant. It takes about five tons of wood to make one ton of diesel. At a wood feed rate of 65,000 MT per year and diesel fuel production rate of 15,000 MT per year, the Beta plant will be one of the largest biomass-based gasifier/FT systems in the world when it is fully operational.

Choren currently has plans to build two more plants, one in France similar in size to the Beta plant, and another larger-scale Sigma plant (1 million MT per year wood, 200,000 MT per year diesel) in Schwedt, Germany. The Sigma plant represents the most economical design and represents what Choren will make available commercially, although they declined to provide cost data as they claim that the actual plant cost depends on the specific project. Choren claims up to an 87% reduction in GHG emissions in their process relative to petroleum diesel.

5.1.2.2 Clearfuels/Rentech

In this team, Clearfuels is the gasification technology provider and Rentech is the FT technology provider. Rentech has a 25% ownership interest in Clearfuels and also owns SilvaGas, which is an alternative gasification technology. The Clearfuels process is better suited for downstream liquid fuels production, while the SilvaGas process is better suited (and has been tested at commercial scale) for heat and power production. The Clearfuels proprietary gasifier design, referred to as High Efficiency Hydrothermal Reformer (HEHTR), is classified as entrained flow and consists of a multi-tubular steam reformer heated externally within a firebox. The system design was developed by Pearson Technologies, Inc., which operated a five TPD (tons per day) pilot-scale system between 1987 and 2007 at their facility in Mississippi. The pilot-scale system included a liquid fuel production system downstream of the gasifier, but much of the early work performed focused on ethanol rather than diesel production. Clearfuels has a license for the fundamental design from Pearson, but has the right to make further changes.

Rentech uses a slurry bubble column FT reactor design with an iron catalyst. It is currently operating a large pilot-scale Product Development Unit (PDU) in Commerce City, Colorado, producing 420 gallons per day of diesel fuel. The PDU FT system has been operating since August 2008 on syngas generated from a natural gas reformer unit. It has accumulated approximately 2,000 hours of intermittent operation over a 22-month period from the time it began operation. However, Clearfuels received a grant from the DOE earlier this year to construct a 20 TPD gasifier to be integrated with the Rentech PDU FT system. The integrated gasifier/FT system is expected to be ready by the end of 2011. Only 7–8 TPD of feed will be necessary to produce the same amount of diesel as is currently being generated. The integrated system will operate on a feed of waste wood, and some contracts have already been established with a local vendor for obtaining tree trimmings from a local power company. This will be the first time that Rentech will have operated an integrated gasifier/FT with biomass feed, although the Rentech staff members who were formerly part of the SilvaGas team bring substantial biomass gasification operational experience.

The Clearfuels/Rentech team is committed to constructing a commercial-scale gasifier/FT system at Hughes Hardwood in Tennessee once the integrated PDU has been tested. This plant will have a 1,000 dry TPD wood feed rate and will produce 16 million gallons per year of diesel. It is expected to be finished in 2014. In addition, Rentech has plans to construct a gasifier/FT system using its SilvaGas gasifier technology in Rialto, California. The system will have a 1,000 dry TPD feed of urban woody green waste and produce 9.4 million gallons per year of diesel along with 35 MW of power. Rentech has stated that the capital cost of a commercial scale system is targeted at $140,000 per barrel per day liquid fuel product capacity, but will not provide any more specific costs without a signed nondisclosure agreement. Rentech claims a 90% reduction in GHG emissions with their integrated process relative to petroleum diesel.

Table 3. Technology Providers for Gasification and FT Processes

Technology Provider	Contact	Gasification					Fischer-Tropsch			
		Gasifier Type	Scale of Current Operations (dry MT/day feed)	CO/H_2 ratio	Hours of Operation	Maximum Process Size Planned (dry MT/day feed)	Reactor Type	Scale of Current Operations (MT/day product)	Hours of Operation	Maximum Process Size Planned (MT/day product)
Choren	Joachim Lischke	Entrained Flow, 3-Stage gasifier (Carbo-V)	186	1	600	2857	Fixed Bed (Shell Process – Sun Diesel)	42.9	0	571
Clearfuels/ Rentech	Eric Darmstaedter (Clearfuels) / Harold Wright (Rentech)	Entrained Flow (High Efficiency Hydro Thermal Reformation)	7.5	1	0	1000	Slurry Bubble Column (RenDiesel)	1.4	2000	147
CUTEC	Stefan Vodegel	CFB	2.7	1.3	2500	68	Fixed Bed (ArtFuel process)	0.00013	900	1
GTI/UPM-Kymmene/ Andritz Carbona	Jim Patel (Andritz)	BFB	18-36	Confidential	Confidential	2857	Not Designed Yet	N/A	N/A	Not Designed Yet
Red Lion Bio-energy/ Pacific Renewable Fuels/REII	Doug Struble (Red Lion)	2-stage BFB (pyrolysis, steam reformer – waste to energy technology)	25	2	Confidential	300	Proprietary (similar to FT)	1	0 (not built yet)	386
RTI	David Dayton	Dual Fluidized Bed	0.5	1 - 2	0	N/A	Not Designed Yet	0.064 – 0.08	N/A	N/A
Stora Enso/ Neste Oil/VTT	Steven Gust (Neste) / Esa Kurkela (VTT)	CFB	60	Varies	8400	1429	Not Yet Determined (either Fixed Bed or Slurry Bubble Column)	1.9	Not Specified	286
TRI	Dan Burciaga	2-step gasifier (indirect heated fluidized bed + carbon trim cell)	4	3	6300	1000	Fixed Bed	0.068	1600	165
TUV	Reinhard Rauch	Dual Fluidized Bed (Fast Internal Circulating Fluidized Bed)	150	1.8	48,256	N/A	Tubular Slurry Reactor (BioFiT Process)	0.0025 - 0.005	6000	N/A
Velocys	Jeff McDaniels, Tad Dritz	Dual Fluidized Bed (Fast Internal Circulating Fluidized Bed)*	150	1.8	48,256	N/A	Microchannel Reactor	0.115	744	203

* Currently using same Güssing gasifier as TUV

5.1.2.3 Clausthaler Umwelttchnik-Institut

Researchers at CUTEC in Germany have developed a small-scale integrated gasifier/FT system referred to as ArtFuel. Their work over the past decade has been mostly focused on determining optimal conditions for both gasifier and FT operation. Examples of some of the areas explored include the effects of feed variation, syngas composition, catalyst type, and reactor stability. The 2.7 dry TPD gasifier is a pilot-scale CFB that utilizes steam, oxygen, and a calcium oxide (CaO) bed additive. The FT design is a fixed-bed reactor with a cobalt catalyst. The lab-scale FT system is much smaller in capacity (150 mL/day) and operates on a slip stream from the gasifier. The gasifier and FT systems can be run together as an integrated system or run independently. The gasifier is typically run only a few days each month with the syngas product stored. The FT system can also run on bottled syngas.

As of June 2010, the gasifier has accumulated nearly 2,500 hours of operation and the FT system has accumulated nearly 900 hours. The system has been run with various types of wood feed (e.g., wood chips, bark, pellets, and sawdust), but most of the focus has been on straw and other forms of residual biomass. There are future plans to upgrade both the gasifier (27–68 dry TPD) and FT systems (100 liters/week). The existing small-scale system is not meant to be economical since it contains an extensive amount of equipment utilized for research purposes.

5.1.2.4 Gas Technology Institute/UPM-Kymmene/Andritz/Carbona

Gas Technology Institute (GTI) is supporting the design of a gasifier/FT system planned by UPM-Kymmene. As part of this work, GTI conducted a series of tests for UPM in 2009 in their existing pilot-scale gasifier system (18–36 dry TPD). The tests were performed at GTI's Flex Fuel Test Facility with a new gas clean-up system developed by Carbona added downstream of the gasifier. The test system did not include FT. The feed consisted of forest residue, bark, and stumps provided by UPM. The purpose of these tests was to generate operating and scale-up data for the full-scale UPM plant design and permitting process. The size of the full-scale integrated plant is anticipated to be 5,000 barrels per day of diesel fuel from a wood (logging residue) feed of 1 million tons per year. Specific operating and cost data resulting from these tests are considered client confidential by GTI and were not provided for this study.

GTI and Haldor Topsoe recently won an award from the DOE to build and demonstrate a liquid fuels production system with the existing gasifier at GTI's facilities. The liquid fuels production system will be based on Haldor Topsoe's Integrated Gasoline Synthesis design that generates synthetic gasoline from syngas via a methanol intermediate. Because this work will not be FT-based, it has not been included in this study.

5.1.2.5 Red Lion Bio-Energy/Pacific Renewable Fuels/REII

The team of Red Lion Bio-Energy and Pacific Renewable Fuels, in collaboration with the Renewable Energy Institute International (REII) recently won DOE funding to build a pilot-scale integrated biorefinery to produce diesel fuel. Red Lion provides the gasification technology, while Pacific Renewable Fuels provides the liquid fuel production technology. Red Lion utilizes a combination of pyrolysis and steam reforming for their gasifier technology, referred to as waste to energy. The system will utilize an existing pilot-scale gasifier (10–25 dry TPD) originally built and located in Denver, Colorado, in 2004 that was moved and has been operating at the University of Toledo, Ohio since April 2008. The gasifier has been used there only for heat and power generation and originally had operated on a coal feed. However, for the DOE-funded project, the gasifier will utilize a feed of agriculture and forest biomass residues. It is claimed that the gasifier can operate on forest residue feed, but it appears that past operation with biomass has focused more on a feed of rice agriculture waste (which is anticipated to be the feed for the first commercial-scale plant).

The diesel fuel production rate anticipated from the pilot-scale system when integrated is 1 TPD. Testing to support this design has been performed at Pacific Renewable Fuels' facility near Sacramento, California. While it is not entirely clear whether the system developed by Pacific Renewable Fuels is in fact based on FT technology, the DOE biorefinery project will require diesel fuel production. Earlier published information suggests that a single catalytic reactor could be used to generate either diesel or ethanol depending on the type of catalyst employed, which could be housed in a cartridge-like manner to make change out easy. It is not clear how practical this approach would be, given that ethanol and diesel have significantly different downstream purification requirements.

The same team of companies plans to build a commercial integrated system for the city of Gridley, California, a major rice growing area, after pilot testing is completed. The commercial plant is slated to process 300 dry TPD of agricultural waste and produce anywhere from 5–42 million gallons per year of diesel fuel as well as electricity. This project is also being funded by the DOE. It should be noted that in December 2009, Red Lion and Pacific Renewable Fuels merged to form a new company called SynTerra.

5.1.2.6 RTI International

RTI International is a research organization based in North Carolina that has developed a syngas clean-up technology. This technology, known as Therminator, consists of a two-stage catalytic system for tar, sulfur, and nitrogen removal from biomass-derived syngas. The system is currently being tested in conjunction with a pilot-scale gasifier at the University of Utah under DOE funding. The gasifier is a dual fluidized bed system that is indirectly heated with steam. Phase one of the test program, which is currently underway, involves validation of the gasifier and Therminator system operation. The recently completed system is currently in the startup and commissioning phase of the project. If successful with respect to tar removal and the level of gas cleanliness achieved, Phase two will involve the addition and testing of a liquid fuels production system. Originally this was scheduled to consist of a slurry bubble column FT reactor, however, RTI has recently stated that due to the high cost of the FT system, a gasoline production technology based on a methanol and dimethyl ether intermediate process may be installed instead. Phase two would be scheduled to last for 500 hours of operation.

The currently configured gasifier and clean-up system utilizes a 0.5 TPD feed of pine wood chips provided by North Carolina State. If Phase two is reached, the liquid fuels production capacity is expected to be approximately 20–25 gallons per day. RTI does not currently have plans for a higher scale integrated system design. RTI has not performed a GHG emission analysis for their design other than looking at some generic results (i.e., not specific to RTI's system) of the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation carbon life cycle model developed by Argonne National Laboratory. No cost data on the system being tested have been made available by RTI.

5.1.2.7 Stora Enso/Neste Oil/VTT

The Finnish companies Stora Enso and Neste Oil have formed a joint venture (NSE Biofuels) to develop and market biomass to liquid fuel conversion technology. The VTT Technical Research Centre of Finland is providing technical support to the project. The team is currently performing testing (referred to as Demo 1) on a system installed at a Stora Enso paper mill in Varkaus, Finland. The system consists of a 60 dry TPD (12 MW) CFB gasifier supplied by Foster Wheeler along with gas clean-up components. A 5 MW slip stream of clean syngas is taken and sent to the FT part of the system. For this Demo 1 system, the focus on the FT portion is only on validating catalyst performance. Thus, the FT design does not represent that intended for a commercial-scale system. FT product is generated at a rate of 1.9 TPD.

In the Demo 1 plant, Stora Enso is providing the location and feed consisting of harvested wood waste. Neste Oil provides further refining of the FT wax product to diesel fuel. The gasifier began operation in June 2009, with the gas clean-up portion operational by the end of 2009. The FT part of the system is currently being commissioned as of June 2010. The decision to move on to Demo 2 will be based on the success of the Demo 1 system and results. If successful, a larger plant will be built at a new location to be determined. This Demo 2 plant will utilize a wood feed rate of 500,000 tons per year to produce 100,000 tons per year of FT wax. The FT reactor design has not yet been determined and may be either a fixed bed or slurry bubble column type. GHG emissions have been estimated at 80%–90% less than fossil fuels. No cost data has been made available by the team.

5.1.2.8 ThermoChem Recovery International

ThermoChem Recovery International (TRI) is based in Baltimore, Maryland, and specializes in gasification technology for the pulp and paper industry. TRI employs a unique, two-stage design for their gasifier which is referred to as Pulse Enhanced Steam Reforming. It incorporates direct steam injection into a fluidized bed. The gasifier is indirectly heated through pulsed combustion heat exchangers that pass through the fluidized bed vessel. The use of pulse combustion technology with a gaseous fuel— typically either a fraction of syngas produced, waste tail gas from downstream, or natural gas— allows for highly efficient heat recovery and transfer. A carbon trim cell downstream of the gasifier allows conversion of carry-over char to adjust the H_2/CO ratio in the syngas.

As part of the awards made by DOE to NewPage Corp. and Flambeau River Papers in its small-scale integrated biorefinery program, TRI is responsible for providing the thermochemical technology. To support these projects, TRI has built an integrated PDU pilot plant located at the Southern Research Institute in Durham, North Carolina. The system has a woody biomass feed capacity of 4 dry TPD. The FT technology utilized for this project is provided by Emerging Fuels Technologies, with TRI being the overall project integrator. The Emerging Fuel Technologies design is a fixed bed reactor using a Co catalyst. The reactor consists of only three tubes but which are at commercial-scale length and diameter. The FT system utilizes a 10% syngas slip stream from the gasifier to produce 21 gallons per day of liquids and wax. The pilot system became operational in stages, with the gasifier coming on-line first in early 2009, the gas clean-up system next in mid-2009, and the FT system in late 2009. As of July 2010, the fully integrated system has been operational for over 1,600 hours, with the gasifier being operational for more than 6,300 hours. To date, current knowledge indicates that this system is the only fully integrated and operational gasifier/FT system of its size operating on a woody biomass feed in the United States.

Testing is ongoing to provide mass and energy balance data to be used as the design scale-up basis for the plants intended for NewPage and Flambeau River Papers. The NewPage plant will have a 500 dry TPD feed rate, producing 5.5–8.5 million gallons per year FT liquids and wax as well as steam and power for use in the mill. The Flambeau River Papers plant will be larger with a 1,000 dry TPD feed rate, producing 16–18 million gallons per year liquids and wax along with steam and power. Both plants are considered demonstration scale despite the high capacities.

The woody biomass feed for the pilot plant consists of slash, mill residue, and non-merchantable wood characteristic of what will be available locally at NewPage and Flambeau River Papers mills. TRI has significant past experience with black liquor feed, having built several commercial-scale gasifiers that run on this feed type. TRI has past experience operating with wood feed in an earlier pilot-scale gasifier at their facility in Maryland, but the current project for DOE is TRI's first experience operating an integrated gasifier/FT system.

5.1.2.9 Technical University of Vienna

The town of Güssing, Austria, along with researchers at the Technical University of Vienna (TUV), has held a prominent position in the area of alternative energy and fuels development for many years. Beginning in the early 1990s, Güssing was the first European community to adopt policies that eventually enabled its entire energy demand to come from renewable resources. A major part of this success came from the design, construction, and operation of a demonstration-scale biomass gasifier to supply heat and power to the community. TUV was part of a team of organizations responsible for establishing the gasifier in Güssing and has maintained a presence for the purpose of testing synthetic liquid and gas fuels development. The gasification technology utilized at Güssing, known as fast internal CFB, was developed at TUV. The gasifier is an 8 MW dual fluidized bed steam blown system and uses a wood chip feed (50–150 TPD) taken from local sources. The gasifier began operation in early 2002 and has been operating ever since, with an accumulated 48,526 hours of operation by the end of 2009.

There are several upgrade technology systems co-located with the Güssing gasifier. TUV has a lab-scale (2.5–5 kg/day) FT system (referred to as BioFiT) that was added in 2005. The FT design is a tubular slurry bed reactor that utilizes a slip stream syngas feed (< 0.5%) from the gasifier. Thus, the Güssing gasifier and FT system together form an integrated and fully operational system. Both cobalt and iron catalysts have been used, but a newly developed cobalt/ruthenium research catalyst has most recently been employed. The FT system has accumulated approximately 4,000–6,000 total hours of operation over all of the experiments performed since its installation, with the longest run on one batch of catalyst being 1,000 hours. As one would expect, the lab-scale FT system is not very economical to operate, having a production cost of about $5000/gal. As a research entity, TUV does not have plans for a commercial-scale integrated system, but it would like to increase the scale of the FT system if funding becomes available. An analysis of GHG emissions from the BioFiT process shows an 80–90% reduction relative to fossil fuels.

The TUV BioFiT system shares the same gasifier syngas feed with another pilot-scale FT system developed and installed by Velocys (see below). TUV also has a small scale methanation reactor system to generate synthetic natural gas (BioSNG) that also shares the gasifier syngas feed.

5.1.2.10 Velocys

Velocys is an FT technology provider that has developed a radically different approach to FT reactor design. Based in Columbus, Ohio, and now a part of Oxford Catalysts Ltd., the Velocys design is a microchannel reactor. Compared to the traditional FT fixed bed or slurry bubble column reactor design, the channels where reaction takes place in a microchannel reactor are 2–3 orders of magnitude smaller in diameter. The small dimensions allow for significantly improved heat and mass transfer, leading to faster rates of production at a higher efficiency and lower cost. A pilot-scale reactor has dimensions of less than 1 m in length and width, compared to traditional FT reactors that are much larger. The basic dimensions of the pilot-scale microchannel reactor remain the same for a commercial-scale unit, with higher capacities generated by stacking reactor units in parallel.

As mentioned earlier, Velocys has recently installed a pilot-scale FT system in Güssing, Austria, that utilizes a slip stream of syngas feed (< 1%) from the existing gasifier. It is co-located with the TUV FT system, although the two are independent of each other and the Velocys FT system is larger. This represents the first integrated system that Velocys has achieved, as all earlier development work and tests were run at lab-scale and only with the microchannel FT technology. SGC Energia provided the gas clean-up technology for the integrated system in Güssing and is responsible for overall project management and plant activities. The FT system has a capacity of 115 kg/day of FT product and achieves 70% CO conversion on a single pass through the reactor. The integrated system first came on-line in May 2010. As of August 2010, the system had been fully operational for over a month. The system will be operated over a wide range of conditions over the next several months to establish and validate its performance. An extended three-month continuous test is also planned.

Velocys does not have a preferred gasification technology partner to work with, although they have had discussions with several vendors. Their FT system has been designed and tested at small-scale with syngas derived from biomass gasification and biomass to liquids (BTL), and from natural gas reforming, or gas to liquids. Velocys has designed a demonstration scale system (10 dry TPD biomass feed, 11 barrels/day FT product) and commercial-scale system (1000 dry TPD biomass feed, 1500 barrels/day FT product), both designed for use with a pressurized gasifier. The estimated capital and operating costs for the demonstration scale plant are $14.6 million and $1.5 million per year, respectively, and the same values for the commercial scale plant are $150 million and $43.3 million per year, respectively. Velocys has also developed its own upgrade technology to transform FT product to refined diesel but it currently is being tested only at lab-scale. Velocys has not done a GHG emission analysis of their process but has relied on other more general life cycle studies on BTL technology.

Because of the very small size of the channels, the microchannel reactor would appear to be particularly sensitive to fouling effects. While Velocys has seen instances of significant fouling in less than 2,100 hours, they have also seen cases where no fouling has occurred after operation for over 9,100 hours. Experiments conducted by Velocys on this issue of fouling potential have shown that maintaining sufficient flow distribution to generate a high wall shear and avoid dead zones is critical to preventing scale formation/fouling. The high shear keeps particles from settling and adhering to the channel walls. Though the exact flow distribution or minimum velocity or shear is not specified by Velocys, attention to these parameters appears to be necessary to mitigate fouling. With regards to durability, Velocys has tested their microchannel reactor design for several thousand hours of successful operation.

A summary of full-scale gasifier/FT plants that are under design and/or construction and expected to be finished within the next few years is included in Table 4.

Table 4. Future Large-Scale Gasifier/FT Plants

Company	Location	Scale	Wood Feed (MT/yr)*	FT Liquid Product (MT/yr)	Expected Completion Date
SilvaGas/ Rentech	Rialto, CA	Commercial	350,000 (dry)	30,268	2012
REII/Synterra	Gridley, CA	Commercial	105,000 (dry)	16,086 – 135,125	2012
NewPage (TRI)	Wisconsin Rapids, WI	Demonstration	175,000 (dry)	17,695 – 27,347	2013
Flambeau River (TRI)	Park Falls, WI	Demonstration	350,000 (dry)	51,476 – 57,911	2013
Choren	CEA, France	Demonstration/ Commercial	168,000 (dry)	23,000	2014
Clearfuels/Rentech	Hughes Hardwood, TN	Commercial	350,000 (dry)	51,476	2014
Choren	Schwedt, Germany	Industrial	1,000,000 (dry)	200,000	2016
Stora Enso/Neste Oil	Finland (Stora Enso mill)	Commercial	500,000	100,000	To be determined after completing demo 1 tests
UPM-Kymmene	To be determined	Commercial	1,000,000	100,000 – 150,000	To be determined

* MT = metric tons

Notable BTL technology providers that were not included in this study because their technology did not meet one or more of the criteria specified in core process #4 (and outlined above) are included in Table 5.

Table 5. Notable BTL Technology Providers Not Included in This Study

Technology Provider	Wood Feed	Gasification/FT Technology	Renewable Diesel or Gasoline	Reason for Exclusion
Energy Research Centre of the Netherlands	√	gasification	X	Milena process focused on synthetic natural gas production
Chemrec	X	√	√	Focused on black liquor feed
Haldor Topsoe, Conoco-Phillips, GTI, UPM	√	X	√	Utilizes non-FT process (Topsoe Integrated Gasoline Synthesis) to generate gasoline via methanol intermediate
Enerkem	√	(catalytic liquid fuel production)	X	Focused on alcohol production
Syntroleum	X	√	√	Focused on waste fat/grease feed
Karlsruhe Institute of Technology	√	X	√	Bioliq process includes pyrolysis prior to gasification; gasoline generation via methanol intermediate

A summary of the size and status of the most current gasifier/FT systems of the technology providers described above that are consistent with core process #4 of this study is included in Table 6. A comparison of operating conditions and selectivity/conversion rate of each gasification technology is presented in Table 7.

Table 6. Status of Gasifier/FT Systems[a]

Technology Provider	Scale (Gasifier/ FT)[b]	Location	Integrated System?	Fully Operational?	Gasifier Feed Rate (MT/day)[c]	FT Product Rate (MT/day)[c]	Status as of mid-2010
Choren	Commercial	Freiberg, Germany	Yes	No	186	43	Gasifier running; FT to be commissioned
Clearfuels/ Rentech	Demo	Commerce City, CO	Not yet	No	7.5	1.4	FT operating with natural gas reformer until gasifier is built
CUTEC	Pilot/Lab	Clausthal-Zellerfeld, Germany	Yes	Yes	2.7	0.00013	Operational
GTI/UPM-Kymmene/ Carbona	Pilot/NA	Des Plaines, IL	No	No	18–36	NA	Gasifier tests only for UPM full-scale design
Red Lion Bio-energy/ Pacific Renewable Fuels/REII	Pilot	Toledo, OH (University of Toledo)	Not yet	No	10–25	1	Gasifier running; liquid fuel production unit to be added
RTI	Pilot	Salt Lake City, UT (University of Utah)	No	No	0.5	0.06–0.08	Gasifier running; FT may be added later
Stora Enso/ Neste Oil/VTT	Demo	Stora Enso Varkaus mill, Finland	Yes	No	60	1.9	Gasifier running; FT now being commissioned
TRI	Pilot	Durham, NC (Southern Research Institute)	Yes	Yes	4	0.068	Operational
TUV	Demo/Lab	Güssing, Austria	Yes	Yes	53–150	0.0025–0.005	Operational
Velocys	Demo/Pilot	Güssing, Austria	Yes	Yes	53–150	0.1	Operational (since 6/10)

[a] Consistent with Route 5 of this study
[b] As specified by technology provider
[c] MT = metric tons

Table 7. Comparison of Operating Conditions and Selectivity/Conversion

Technology Provider	**Overall Yield: FT Product/ Wood Feed**	**Gasification**			**Fischer-Tropsch**		
		Temperature (°C)	**Pressure (bar)**	**Conversion: Syngas Yield (SY)[a], Carbon Conversion (CC), or Cold Gas Efficiency (CGE)[b]**	**Temperature (°C)**	**Pressure (bar)**	**Conversion: CO Conversion Per Pass**
Choren	23%	Low T stage: 400–500 High T stage: 1300–1550	6	77% (SY)	~ 250	30	70%
Clearfuels/ Rentech	18%	982	28	71% (CGE)	204–232	28	80%
CUTEC	0.024%	950	1		150–350	5–40	
GTI/UPM-Kymmene/ Andritz Carbona	N/A	Confidential (850–930)[c]	Confidential (2–27)[c]	Confidential	Design not specified yet	Design not specified yet	Design not specified yet
Red Lion Bio-energy/ Pacific Renewable Fuels/REII	4%	≤ 927	≤ 4.4	91% (SY)	Proprietary	Proprietary	Not provided
RTI	16%	650	2.4	98–99% (CC)	Design not specified yet	Design not specified yet	Design not specified yet
Stora Enso/ Neste Oil/VTT	7.5%	600–1000	10	"very high"	Not provided	Not provided	"Not too high"
TRI	17%	788	3.4–5.4	97–98% (CC)	193–216	25–28	60–70%
TUV[d]	0.8%	850–1000	1	70% (CGE)	250	20–30	90%[e]
Velocys[d]	21%	850–1000	1	70% (CGE)	210–225	25	> 70%

[a] Syngas yield = mass of syngas (CO + H_2) produced/mass of dry wood feed
[b] Cold gas efficiency = heat value of syngas produced/heat value of wood feed
[c] Values for specific testing are confidential; those cited represent general capabilities of GTI gasifier
[d] Gasifier data are for Güssing gasifier, currently shared by TUV and Velocys
[e] Includes recycle of tail gas with reformer

5.2 Pyrolysis Pathway

5.2.1 Hybrid Poplar

Hybrid poplars are fast-growing trees that are crosses between native cottonwood trees. They are bred specifically for SRWCs for the purpose of supplying pulp fiber or logs for engineered wood products such as panel board or oriented strand board.[19] The motivation for developing SRWCs such as hybrid poplars came as a result of an anticipated shortage of wood fiber for the paper industry. In regions such as western Canada and the upper Midwest of the United States, the transportation distance between the wood supply to the plants was huge. In addition, these plants often depended on residual chips and sawdust from area lumber mills that proved to be a very inconsistent supply of wood fiber. In the 1970's, some papermakers identified the use of SRWCs as a means of providing a consistent supply of fiber. At the same time, there was a market shift that demanded an increase in paper that was produced from hardwood fiber.[20] These factors led to the widespread interest in the development of hybrid poplar.

The rotation time for hybrid poplar is typically 8–12 years. This is the length of time required to grow the tree to the point where the quality of fiber in the wood is acceptable and the point where the highest value can be extracted from the entire biomass.[21] However, due to the increased interest in using these trees as a feedstock for bioenergy production, different research groups began to evaluate the use of hybrid poplar under a shorter rotation time. Issues such as disease resistance, growth rates, number of harvests per planting, and methods of harvesting were thoroughly evaluated. One interesting point that was made numerous times was that the issue of raw material storage went away since the tree farms act as a living storage and that harvest could be performed on a just-in-time basis.[22]

Disease resistance appears to be a major issue with hybrid poplar trees, especially under a short rotation scenario. In addition, recent findings indicate that only three rotations can be obtained with hybrid poplars. This dramatically affects the economics of hybrid poplar as the plantings will represent a significant cost to the system. For these reasons, researchers are turning to willow as a potential SRWC as it does not have many of the issues associated with hybrid poplar.[23]

Some notable organizations working in the hybrid poplar space include:

- **Greenwood Resources**. Greenwood Resources is based in Boardman, Oregon, and currently operates over 9,300 hectares, or 22,980 acres, of hybrid poplar in the Pacific Northwest. Currently, they are operating on a 15-year rotation with the output going into the saw log market. Greenwood Resources recently signed an agreement with ZeaChem, a cellulosic ethanol company, to supply them with feedstock from their hybrid poplar farm. The plan is to harvest the trees as scheduled, and the tree tops, small branches, and leaves will be chipped and sent to ZeaChem.[24] Although this product typically qualifies

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[19] Poplar Council of Canada National Report 2008, Final Version 15
[20] Stanton, B. et al, " Hybrid Poplar in the Pacific Northwest," Journal of Forestry, June 2002
[21] Personal communication, Michelle Sulz, Alberta-Pacific Forest Products, August, 2010
[22] Personal communication, Jake Eaton, Greenwood Resouces, July 2010
[23] Personal communication, Tim Volk, State University of New York, July 2010
[24] Personal communication, Brian Stanton, Greenwood Resources, August, 2010

as mill or forest residue, it represents the only current link between the hybrid poplar industry and the biofuel industry.

- **Alberta-Pacific Forest Products**. Alberta-Pacific Forest Products, also known as Al-Pac, has begun to lease more than 8,000 hectares (19,768 acres), in Alberta, Canada, to grow hybrid poplar trees to feed its pulp mills. Currently, it is not harvesting any wood, and concedes that this may result in a very expensive source of fiber; however, the company felt that this was a necessary step to ensure fiber supply due to the deforestation activities in Alberta as a result of the development of the Tar Sands. The company plans to operate on an 18-year cycle.
- **Catalyst Paper/Pacifica Poplars**. Pacifica Poplars, which was established by Catalyst Paper, planted 200 hectares, or 4,942 acres, of hybrid poplar as an experiment. The company encountered numerous problems, including disease and blow-down from wind and has since canceled the experiment.[25]

5.2.2 Pyrolysis

As mentioned earlier, fast pyrolysis is a process that utilizes high temperature in the absence of oxygen at a rapid heat transfer rate such that the production of condensable vapors as a decomposition product is favored. Once condensed, the resulting liquid (known as pyrolysis or bio-oil) is dark brown, acidic, and has a heat value approximately half of typical fossil fuels.

The majority of work in pyrolysis to date has been in the development of an ideal pyrolysis reactor. The ideal pyrolysis reactor should:

- Maximize bio-oil production while at the same time yield pyrolysis oil that is low in solids, stable, neutral in pH, low in water, and high in heat value.
- Minimize the amount of pre-treatment required for the feed. Typically, pyrolysis reactors require the feed material to have a particle size as small as 2 mm. The larger the particle size, the smaller the capital and operating costs of the entire system.
- Achieve economy of scale at rates such that these systems can be deployed remotely and minimize the transportation costs of the biomass.
- Minimize downtime required to maintenance.

To date, seven different reactor types have been pursued by a variety of different technology providers. These are:

- Ablative reactor
- Auger reactor
- Bubbling fluidized bed
- Circulating fluidized bed
- Rotating cone reactor
- Vacuum reactor
- Catalytic pyrolysis reactor

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[25] Poplar Council of Canada, Laura Walz, Peak Online “Poplar strategy unpopular,” 2/14/2007

In the ablative reactor, wood particles are fed onto a hot disc. The concept is analogous to feeding a stick of butter onto a hot frying pan. As the wood is being fed, it quickly vaporizes as it is touching the plate. This design allows for considerable larger feed into the reactor, such as boards or wood chips. In an auger reactor, the biomass is fed onto heated screws that provide both the heat transfer required as well as to convey the material forward. [26]

Similar to a bubbling fluidized bed reactor, in a circulating fluidized bed reactor, hot sand is contacted with the biomass particles at a fast heat transfer rate. However, in a circulating fluidized bed, the resulting char and sand is entrained out of the reactor and sent to a combustion chamber where the char is burned. This allows for a simple way to re-heat the sand using the char that results from the process.[27]

In a rotating cone reactor, hot sand particles are mixed with the biomass using a rotating cone as opposed to an inert carrier gas. The idea was to blend the attributes of the ablative reactor with those of the circulating fluidized bed reactor. The sand and char particles are removed and burned to re-heat the sand. [28]

The vacuum reactor is a deviation from traditional fast pyrolysis. Under these conditions, the rate of heat transfer is between that of slow and fast pyrolysis, hence, the bio-oil yield is about half of that yielded by typical fast pyrolysis processes. However, the process remains of interest as the design inherently allows for larger particles to be fed into the reactor, while at the same time, the resulting pyrolysis oil has a heat value that is about 50% higher than that yielded from typical fast pyrolysis processes.[29]

In catalytic fast pyrolysis, a catalyst is mixed with the biomass under fast pyrolysis conditions. The presence of the catalyst facilitates reaction that favor pyrolysis oils that have reduced water content, are miscible with crude oil, and have neutral pH. Based on a recent patent application assigned to KiOR, Inc., the process appears to be that of a bubbling fluidized bed where the catalyst is introduced in lieu of sand.[30,31]

5.2.3 Pyrolysis Technology Providers

Work on pyrolysis is distinctly divided into two groups:

1. Universities and research laboratories that are focused on fact finding and analysis;
2. Technology providers who are focused on the commercialization of the technology and often license technology from the universities and research laboratories.

Table 8 shows the current technology providers in the area of pyrolysis.

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[26] Venderbosch, R.H., Prins, W., Biofuels, Bioproducts & Biorefining 4:178-208 (2010)
[27] Venderbosch, R.H., Prins, W., Biofuels, Bioproducts & Biorefining 4:178-208 (2010)
[28] Venderbosch, R.H., Prins, W., Biofuels, Bioproducts & Biorefining 4:178-208 (2010)
[29] Venderbosch, R.H., Prins, W., Biofuels, Bioproducts & Biorefining 4:178-208 (2010)
[30] Venderbosch, R.H., Prins, W., Biofuels, Bioproducts & Biorefining 4:178-208 (2010)
[31] Venderbosch, R.H., Prins, W., Biofuels, Bioproducts & Biorefining 4:178-208 (2010)

Table 8. Pyrolysis Technology Providers

Technology Provider	Reactor Technology
BTG	Rotating cone
PyTec	Ablative
Dynamotive	Bubbling fluidized bed
Ensyn	Circulating fluidized bed
Anellotech	Catalytic pyrolysis
New Earth Renewable	Vacuum
ABRI-Tech	Auger
KiOR	Catalytic pyrolysis
Gas Technology Institute	Catalytic pyrolysis

5.2.3.1 Biomass Technology Group

Biomass Technology Group (BTG) is based in Enschede, Netherlands, and has commercialized the rotating cone reactor. The original idea for the rotating cone reactor was developed by R.M. Wagenaar at the University of Twente in 1989 and since then, BTG has continued the research and development work on the reactor. The first pilot plant was constructed in 1997 and operated at a rate of 110 lb/h In 2001, BTG successfully scaled the system to process rates of 250 kg/h. In addition to scaling the size of the system, BTG was also able to increase the particle diameter of the feed, going from a nominal diameter of 1–10 mm today. The company also claims to have produced more than 100 MT of bio-oil from more than 50 different materials.

In 2004, BTG sold its first commercial plant to Genting Bio-Oil Sdn Bhd in Malaysia. The system was designed to process 50 MT per day of empty fruit bunch (EFB), a by-product of palm oil processing. The plant started up in 2005 and has been running continuously since then. Some notable observations from this plant are:

- The bio-oil produced is co-fired in a slow speed diesel generator that is located over 300 kilometers away.
- The EFB enters into the plant at 50% moisture and is dried down to 5% moisture using waste heat from the pyrolysis process.
- The plant is operating at 85% of design capacity.
- Erosion-related problems from high velocity sand were observed.
- There was considerable wear on the pre-treatment equipment for the EFB.

This year, construction has started at a 120 metric ton/day wood-based pyrolysis plant in Hengelo, Netherlands, by Empyro using BTG’s rotating cone reactor technology.

5.2.3.2 PyTec

PyTec was founded in 2002 and is based in Hamburg, Germany. PyTec is developing the ablative pyrolysis technology and has a 6 metric ton/day plant in operation in Hamburg and plans to construct a 50 MT/day plant in Malliss, Germany. Their business plan is based on locating their plants in remote locations, and hence it is envisioned that their design can be economical at rates as low as 1 metric ton per hour. Due to limitations inherent in the design, they believe that the largest single unit they can make will have a capacity of 1.6 MT per hour. This means that rate above that number will require multiple process lines.

One of the attributes of the ablative reactor is the ability to take larger feed sizes, hence reducing the requirement for size reduction. Currently, PyTec's systems are designed to be fed boards that have a cross-sectional area of 10 mm × 46 mm, and a length of 350 mm. The feed rate is 4 mm/s.

The Hamburg plant now operates 24 hours a day and is primarily processing spruce wood chips. It is envisioned that the primary use for the bio-oil produced in these plants will be for generating power in low speed diesel engines.

5.2.3.3 Dynamotive Energy Systems

Dynamotive Energy Systems was founded in 1990 and is based in a suburb of Vancouver, Canada. In 1996, the company began an initiative to commercialize a fast pyrolysis technology based on a bubbling fluidized bed design that was originally developed at the University of Waterloo. In 2005, the company started up a 100 metric ton/day plant in West Lorne, Ontario. The West Lorne plant is co-located with Erie Flooring who supplies sawdust to the plant. The West Lorne plant has been the primary plant that Dynamotive has used for product demonstrations. The plant did suffer a fire in 2008 and was down for over three months as a result. In 2007, Dynamotive completed a second plant in Guelph, Ontario, that is rated for 200 MT/day. Although both plants are owned by Dynamotive, it has been reported that the West Lorne location is in receivership and that the assets are being sold.[32] The Guelph plant has been in shut-down mode since 2008 due to feedstock and financial issues.[33]

5.2.3.4 Ensyn

Based in Ottawa, Ontario, Ensyn Technologies was founded in 1984 to commercialize rapid thermal processing, which was developed at the University of Western Ontario. The technology is based on the circulating fluidized bed concept. Commercialization of Ensyn's technology was facilitated through the granting of an exclusive license to Red Arrow Food Products Company in Wisconsin for the production of Liquid Smoke. Through this arrangement, significant run time and experience was obtained that helped the development of the technology.

Ensyn reports that there are seven plants in commercial operation today utilizing their technology. The plants are located in the United States and Canada. Completed in 2007, the largest plant is owned and operated by Ensyn, is located in Renfrew, Ontario, and is rated at 100 MT per day. The seven plants have a plant availability of over 90%.

In July 2010, Ensyn received an order from Tolko, a major pulp and paper company, to supply a 400 metric ton per day fast pyrolysis plant that will be co-located at Tolko's High Level, Alberta facility. This plant will supply bio-oil that will be used to generate heat and electricity. Ensyn has also been selected by the DOE to supply a fast pyrolysis demonstration system at Tesoro's refinery in Kapolei, Hawaii.

In March 2009, Ensyn and UOP created a joint venture called Envergent. The objective for Envergent is to combine Ensyn's fast pyrolysis technology with UOP's upgrading technology to commercialize the use of fast pyrolysis for the production of fungible liquid fuels.

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[32] London Free Press, "Green gem goes bust:, July 9, 2010

[33] Dynamotive Energy Systems Annual Report, 2008

5.2.3.4 Anellotech

Anellotech is a start-up company based in New York City that plans to commercialize the catalytic pyrolysis technology being developed by Dr. George Huber at the University of Massachusetts. The core concept is to perform fast pyrolysis in a bubbling fluidized bed reactor in the presence of a zeolite catalyst. The result is a mixture of aromatics consisting primarily of benzene, toluene, and xylene and whose boiling point range is identical to that of gasoline. Today, the operation is lab-scale; however, the company plans to have a commercial plant by 2014.

5.2.3.5 New Earth Renewables

New Earth Renewables is a start-up company based in Seattle, Washington, that purchased the assets of the former Pyrovac Institute located in Jonquiere, Quebec. The equipment is a 100 metric ton/day vacuum pyrolysis plant designed and built by Dr. Christian Roy, who pioneered the concept of vacuum pyrolysis. Due to project financing, the plant is not running today, however, when Pyrovac Institute was running, the plant logged over 2,000 hours of operation. Numerous products were processed through the plant, however, at the time, most of the focus was on bark and tire rubber chips.

The vacuum pyrolysis process differs from traditional fast pyrolysis in the sense that the reaction time is considerably longer. Whereas fast pyrolysis takes place in seconds, vacuum pyrolysis takes minutes and the reaction takes place at 20 kPa. The advantages of vacuum pyrolysis are a 50% increase in heat value of the pyrolysis oil and the ability to process larger particles (2.5 cm for New Earth versus 0.5 cm for Ensyn). However, the disadvantages are that the oil yield is considerably smaller, at least a 50% reduction in bio-oil production. Although the bio-oil appears to be more stable, there has been no work performed to prove that it is any easier to process into a refinery feedstock.

5.2.3.6 ABRI-Tech

ABRI-Tech is a joint venture between Advanced BioRefinery, Inc., and Forespect, Inc. They have developed a fast pyrolysis system that is based on an auger reactor. They are currently offering for sale units of 1 metric ton/day and 50 metric ton/day capacity. They also have a 0.5 ton/day research unit. The information that we were able to obtain about this process came from either their website, or from a paper published by Badger in 2006.[34] The team has not been successful in contacting the company for more information.

5.2.3.7 KiOR

KiOR was founded in 2007 as a joint venture between Khosla Ventures, a San Francisco-based venture capital firm run by Vinod Khosla, and BIOeCON, a research company based in the Netherlands. The core of KiOR's technology is called biomass catalytic cracking which in theory is a catalytic pyrolysis process. The key to their technology is a method that combines bubbling fluidized bed technology with the use of a catalyst in a fashion similar to how sand is used in these types of reactors to simultaneously grind and heat the material, while at the same time exposing the material to a catalyst to facilitate conversion to bio-oil.

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[34] P.C. Badger, Biomass & Energy 30 (2006) 321–325

KiOR recently made headlines, announcing that it had raised $110 million in funding and plans to commit $500 million to build three of five plants in Mississippi in exchange for a multimillion dollar incentive package from the state that includes a $75 million dollar load. The KiOR operation in Houston has logged over 4,000 hours of operation and is now processing 10 MT/day of wood chips to produce 15 barrels of upgraded bio-oil. Although we did not get the specific analysis, KiOR claims that the bio-oil is neutral in pH and fully miscible with crude oil.

5.2.3.8 Gas Technology Institute

In operation for more than 65 years, GTI is a not-for-profit research and development organization located outside Chicago, Illinois. Recently, GTI added a former UOP employee, Terry Marker, to develop and commercialize a novel catalytic pyrolysis process called "Integrated Hydropyrolysis and Hydroconversion" (IH^2). In this process, fast pyrolysis of biomass takes place in the presence of H_2 and catalyst at pressures between 14 to 35 bar. The reactor is immediately followed by an integrated hydroconversion step. The resulting product is very low in water and oxygen, has three times the heating value of typical pyrolysis oil, and is fully compatible with crude oil. Although GTI has made numerous calculations showing the economics of this process at commercial scale, the current operation is lab scale.

The recent order for a large-scale pyrolysis plant in Canada certainly suggests that at least, the circulating fluidized bed technology is at a commercial level.[35] However, it remains to be seen how the overall costs of operation with regards to balancing the pre-treatment of biomass with the cost of the pyrolysis reactor itself. Erosion from the recirculation of material and corrosion from the acids in the pyrolysis oil are factors that need to be considered. For widespread use as a technology for the production of liquid fuels, the issue of producing a pyrolysis oil that is easily stabilized and upgraded remains the biggest opportunity for the development of pyrolysis.

5.2.4 Pyrolysis Oil Upgrading

Aside from the progress made as a result of catalytic pyrolysis, there remains a significant effort to develop an upgrading process that can convert traditional pyrolysis oil into a material that is not corrosive, has a lower water and oxygen content, and can be used in traditional petrochemical refineries. To achieve this, there are numerous challenges to overcome:

1. Pyrolysis oil exists as a micro-emulsion with water and is highly oxygenated.
2. Pyrolysis oil is immiscible with petroleum crude oil.
3. Pyrolysis oil is very acidic, usually in the range between 2–2.5 pH. Twenty-one percent of its mass consists of organic acids such as acetic acid, formic acid, and propionic acid.[36]
4. Pyrolysis oil is very unstable and increases in viscosity over time. It is believed that a number of reactions occur with bio-oil that result in storage instability.[37] These reactions include:

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[35] http://biofuelsdigest.com/bdigest/2010/06/08/ensyn-tolko-to-build-worlds-largest-fast-pyrolysis-plant-in-canada/

[36] Tony Bridgewater, "Fast pyrolysis based biorefineries," American Chemical Society Annual Meeting, Washington, D.C., August 31, 2005

[37] Diebold, J.P., "A Review of the Chemical and Physical Mechanisms of the Storage Stability of Fast Pyrolysis Bio-Oils," NREL/SR-570-27613, January 2000

   a. Organic acids with alcohols to form esters and water (esterification)
   b. Organic acids with olefins to form esters (esterification)
   c. Aldehydes and water to form hydrates (hydration)
   d. Aldehydes and alcohols to form hemiacetals (hemiacetal formation), or acetals and water (acetalization)
   e. Aldehydes to form oligomers and resins (homopolymerization)
   f. Aldehydes and phenolics to form resins and water (transacetalization)
   g. Aldehydes and proteins to form oligomers (dimerization)
   h. Organic sulfur to form oligomers (alcohol addition), and
   i. Unsaturated compounds to form polyolefins (olefinic condensation).

5. Pyrolysis oil contains numerous functional groups including acids, aldehydes, ketones, carbohydrates, furans, pyrans, aromatics, and hydrocarbons, all of which co-exist in the liquid. In 2005, a group led by Tony Bridgewater of Aston University identified over 162 different chemicals in pyrolysis oil.[38] This diversity makes upgrading all the more difficult. Furthermore, the proportions of these groups can vary depending on the feedstock used for fast pyrolysis.

At present, all the work being done on pyrolysis upgrading is being performed at the lab scale. In October 2008, DOE funded five projects for the stabilization of bio-oil. Project recipients were:

- **UOP**, who partnered with Ensyn, the National Renewable Energy Laboratory, Pacific Northwest National Laboratory (PNNL), and the U.S. Department of Agriculture Agricultural Research Service. The project objective is to review prior work and identify the best technology for further development. It is believed that this technology is based on the two step hydrotreating and hydrocracking upgrading process developed at PNNL using UOP's proprietary catalyst and technology. Recently published data using mixed wood, oak, corn stover, and poplar as a feedstock report an overall oil yield of 37%–54% (on a dry feed basis) and H_2 consumption of 490–710 liters of H_2 consumed (standard temperature and pressure basis) per liter of bio-oil (Elliott et al. 2009).
- **RTI International**. The focus of this project is to develop highly active and stable catalysts for the stabilization of bio-oil through catalytic deoxygenation of the biomass-derived pyrolysis vapors prior to condensation. This is similar to the concept being pursued by GTI. For this report, the team has not been able to find any information on this specific project. According to Dave Dayton at RTI International, this project is still being developed.
- **Virginia Polytechnic University**. This work is based on the fractional catalytic pyrolysis work that Dr. Foster Agblevor has been pursuing for the past several years. The concept behind this work is to use catalysts to perform in situ conversion of biopolymers into desired products. Using hybrid poplar as a feedstock, Dr. Agblevor's team demonstrated that lignin compounds could be converted into cresols and phenols, while carbohydrates

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[38] Tony Bridgewater, "Fast pyrolysis based biorefineries," American Chemical Society Annual Meeting, Washington, D.C., August 31, 2005

are converted into gaseous products[39]. Although the liquid yields are lower than that of fast pyrolysis, the resulting bio-oil had a high heating value of 30.5 MJ/kg and was immiscible in water.

- **University of Massachusetts**. This project will combine membrane and catalyst technology to produce a bio-oil that can be used in petroleum infrastructure. In a presentation to the Boston chapter of the American Institute of Chemical Engineers, Dr. George Huber showed that microfiltration can be used to remove char out of the bio-oil, which should improve stabilization. The first paper on this work is in revision and is expected to be published soon.
- **Iowa State University**. Iowa State University has partnered with ConocoPhillips to develop four distinct innovations to improve bio-oil stability. These include addressing biomass pretreatment, filtering of bio-oil vapors, fractionating the bio-oil, and using a catalyst to process the bio-oil fractions. A company called Avello Bioenergy was created to commercialize these developments. Unfortunately, the university would not give any information on the process or progress without a non disclosure agreement.

In addition to the organizations named above, Mississippi State University and Dynamotive Energy Systems have also maintained an active program in bio-oil upgrading.

- **Mississippi State University** has been developing a two step, hydrotreating/ hydrocracking production system similar to the system developed at PNNL. Mississippi State has also developed a proprietary hydrodeoxygenation catalyst that they claim will yield 1.1 barrel of upgraded bio-oil from one short ton of biomass. The resulting bio-oil has properties similar to diesel fuel.
- **Dynamotive Energy Systems** had announced in October 2009, the development of a bio-oil upgrading process they call Biomass INto GasOil (BINGO). This process is described as a two-step process involving hydrotreating and hydrocracking. Dynamotive has not published any information regarding the quality of the oil. It is believed that the process is lab-scale. In June 2010, Dynamotive announced that they had signed a memorandum of understanding to cooperate in the field of bio-oil upgrading with IFP, a public sector research and development center located in France. The team was not able to attain any information about the specifics of the process, including patents or patent applications.

Furthermore, DOE funded an additional three projects in September 2010 for bio-oil upgrading:

- **W.R. Grace**. This project will focus on the development of both catalysts and catalytic reactors for bio-oil upgrading.
- **PNNL**. This three-year project will be a collaboration with Albermarle and UOP to upgrade bio-oil.
- **Battelle Memorial Institute**. This project will develop catalysts and an integrated process to upgrade bio-oil. The objective is to get at least 1,000 hours on a single charge

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[39] Agblevor, F.A., Beis, S., Mante, O., Abdoulmoumine, N., "Fractional Catalytic Pyrolysis of Hybrid Poplar Wood," *Ind. Eng. Chem. Res.* 2010, 49, 3533–3538

of catalyst and upgrade the bio-oil such that up to 30% can be incorporated into crude oil feed to the refinery.

In Europe three main initiatives are underway to upgrade pyrolysis oil:

- **BIOCOUP**. The BIOCOUP project is a consortium consisting of 17 different European organizations and whose objective is to develop processes that would allow biomass-based feedstock to be co-fed into a conventional oil refinery. The project is supported by the Sixth Framework Programme (FP6). To date, the group has studied three upgrading strategies for bio-oil. The processes are hydrodeoxygenation, high-pressure thermal treatment, and decarboxylation. The project team has reported good progress on hydrodeoxygenation and decided that high-pressure thermal treatment and decarboxylation are not suitable for upgrading. Catalyst development has been based on using pentanoic acid as a model component, as opposed to using bio-oil directly. The team is building two process development units for pilot plant testing, and will have a capacity of 1 kg/h.
- **Catal International**. This consortium, consisting of CARE, Ltd, and Aquafuels Research, Ltd., is funded by the Carbon Trust as part of their pyrolysis challenge. Over 7 million pounds will be spent in 3–4 years to develop an end-to-end process that uses pyrolysis to convert organic waste into fuel that can be used in today's infrastructure. The project description does not identify specifics on their approach.
- **York Green Chemistry Centre (University of York)**. This project is also funded by the Carbon Trust and requests that 500,000 pounds be spent on developing a low temperature, microwave-based process that produces upgraded bio-oil.

The biggest opportunity for improvement remains the ability to scale a process that can stabilize and upgrade pyrolysis oils into liquid fuels that are truly fungible with today's infrastructure. The promise of catalytic pyrolysis suggests that this may, in fact, be the best route from a product specification point of view, however, demonstrating the ability to scale as well as achieving the necessary costs are the biggest challenges. Much discovery work lies ahead to bring this process to commercialization.

6 Task 2 Results

6.1 Subtask 2.1 Results

It was determined that the simplest way of graphically depicting the biomass-to-fuel processes is to express them as the following three simple process blocks in series:

- Growing/harvesting (hybrid poplar or forest residue)
- Conversion (fast pyrolysis or gasification)
- Upgrading (bio-oil upgrading or FT synthesis).

Figure 3 and Figure 4 show the simplified block diagrams for core process #4 and #5 respectively.

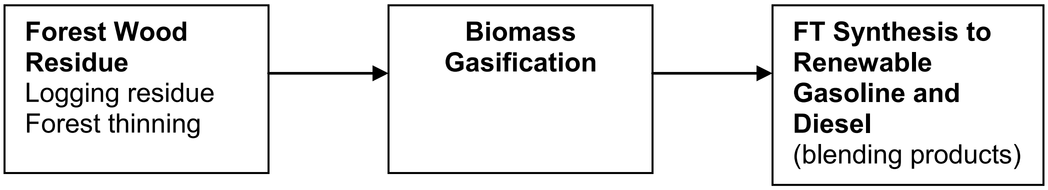

Figure 3. Core Process #4 simplified block flow diagram

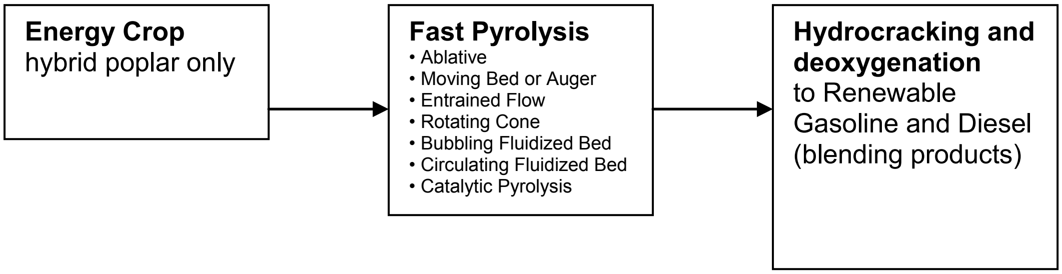

Figure 4. Core Process #5 simplified block flow diagram

Based on the precedent established by the DOE for the integrated biorefinery projects as well as discussions with NREL's staff, it was decided that the key metric components for evaluating processes can be reduced into the following groups:

- Scale of operation
- Key performance factors, such as yield, energy use, and hours of operation
- Key economic factors, such as unit operating and capital costs
- Fidelity, or degree of process integration
- Feed characteristics
- GHG reduction.

Using these groups, the team established the data that needed to be collected for the different groups. For the growing/harvesting block, the data of interest were:

- Scale, including:
    - Size of operation (hectares)
    - Scale of operation (MT/yr)
- Key performance factor, including:
    - Yield (MT/ha-yr)
- Key economic factor, including:
    - Cost ($/MT)

For the Pyrolysis/hydrotreating block, the data of interest were:

- Scale, including:
    - Scale of current operations (MT/yr)
    - Maximum process size (MT/yr)
    - Scale at which data was obtained (MT/yr)
- Key performance factor, including:
    - Yield (% product/feed)
    - Percent Btu product/Btu feed
    - Percent parasitic load
    - Process uptime
    - Total hours of operation
    - Feed size
- Key economic factor, including:
    - Dollars per gal/yr – capital expense
    - Dollars/million Btu of fuel
    - Dollars/million Btu of product
    - Dollars/million Btu product – variable expense
- Fidelity, including:
    - Integration with feed
    - Integration with product
- GHG reduction (%), including:
    - Feed with hybrid poplar

For the Gasification/FT synthesis block, the data of interest were:

- Scale, including:
    - Scale of current operations (MT/yr)

    - Maximum process size (MT/yr)
    - Scale at which data was obtained (MT/yr)
- Key performance factor, including:
    - Yield (% product/feed)
    - Percent Btu product/Btu feed
    - Percent parasitic load
    - CO/H_2 ratio
    - Total hours of operation
    - Process conditions
- Key economic factor
    - Dollars per gal/yr – capital expense
    - Dollars/million Btu of fuel
    - Dollars/million Btu of product
    - Dollars/million Btu product – variable expense
- Fidelity, including:
    - Integration with feed
    - Integration with product
- GHG reduction (%), including:
    - Feed with forest residue

6.2 Subtask 2.2 Results

Using the data gathered that was collected under Task 2.1, a methodology was developed to convert the data into a SOT readiness level. Using the publication entitled, "Technology Readiness Assessment/Technology Maturation Plan Process Guide," March 2008, from the DOE Office of Environmental Management, a matrix was developed that would score the categories based on the data that was received. For this exercise, the team would evaluate the technology from two perspectives:

- The technology readiness level (TRL) for the individual blocks
- The TRL for the end-to-end process. The TRL for the end-to-end process was defined to be the average of the TRL for the three blocks individually. In the event that a process only has two blocks, as would be the case for catalytic pyrolysis since the conversion and upgrading take place in the same block, the TRL is then the average of the two relevant blocks.

The first step in methodology development was to determine the technology readiness criteria, or more specifically, which data should contribute directly to technology readiness. For the hybrid poplar and forest residue block, the technology readiness criteria that were used include:

- **Current production rate** (MT/year). This criterion is justified since it provides an indication of how relevant the process is to a commercial operation.
- **Area of growing/harvesting** (hectares). This criterion is justified since this also provides perspective on the relevance of the operation to supplying a commercial-scale plant.
- **Yield/hectare** (MT/ha-yr). This criterion is important as it benchmarks the operation in terms of yield against others in the industry. One caveat about this criterion is that the yield is also a function of location, and not just the practice utilized. Hence, a low yield observed at a given operation is not necessarily a reflection of the state of technology, but rather, a function of the attributes of a given location.
- **Fidelity**. This criterion is important as it is a reflection of the degree of integration between the growing/harvesting operation, and the ultimate end user.

The scoring matrix for growing/harvesting is shown in Table 8.

Table 9. Scoring Matrix for Growing/Harvesting

Score	Scale (MT/yr)	Area (Hectare)	Yield (MT/ha-yr)	Fidelity
9	Full >17,500 MT/yr	1167	15+	Identical
6	Demo 1,750–17,500	116.7	10–15	Similar
5	Pilot 175–1,750	11.7	5–10	Pieces
3	Lab 0> Lab > 175	>1.17	<5	Simulated
1	Paper 0	n/a	n/a	Paper

By definition, the TRL cannot be higher than nine, or lower than one. Furthermore, by definition, if the scale of an operation can only be described as a paper study, the overall TRL cannot be greater than one.

The ranges for scoring the TRLs were developed by evaluating both the range where full scale of the technology is achieved, as well as relevance against the criteria as defined in the DOE document. Since this score is to reflect the state of technology, and not the attractiveness of the technology, it is appropriate to use ranges as a scoring criterion. For example, a technology that is fully developed may not be economically feasible. Hence, is it important to evaluate where a technology is developmentally as well as its feasibility. This scoring is also useful because it can indicate if there is room for improvement, and therefore a smart technology investment.

The scale of operation was based on the fact that most pyrolysis and gasification systems are considered to be at full scale when they are processing 50 MT/day or above. Assuming that the plant operates at 350 days per year will require a supply of 17,500 MT/yr. It was then decided that a factor of 10 was the appropriate scaling factor between different size plants.[40]

The area required was based on similar criteria. From numerous conversations with growers, a basis of 15 MT/ha/yr was a typical yield that growers wanted to achieve. Applying this yield to the annual requirement of 17,500 MT/yr amounts to an area requirement of 1,166.7 hectares (23,000 acres). Hence, this was used as a basis for full scale, and the remaining criteria were simply factors of 10 less.

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[40] Adapted from PYNE IEA Bioenergy www.pyne.co.uk.

For the yield, the same basis that was used as the starting point for determining area was used as the basis for full scale. Based on data from different growing and harvesting operations, distinct groups emerged, suggesting that a reduction of 5 MT/ha/yr was an appropriate gap between different readiness levels. As discussed earlier, although the yield is often a function of the growing region, new species and technology are being developed to normalize the expected yield across all regions. This is similar to the development that has been observed for corn hybrids, where considerable effort is made to apply breeding technology to maximize corn yields in all regions where it is grown. Reduced yields can also be a function of the hybrid selection, where certain species may be more resistant to disease and pests than others.

Fidelity is a reflection of the degree of integration in which the growing or harvesting operation is integrated with the process. The words chosen to describe the degree fidelity were the same words that were in the DOE document. By definition:

- **Identical** means that the system matches the final application in all respects. For example, if a hybrid poplar farm were directly producing wood chips for use in an integrated biorefinery, this rating would be "Identical."
- **Similar** means that the system matches the final application in almost all respects. For example, if a hybrid poplar farm were producing woodchips for a biomass-fed power plant and included drying and grinding the woodchips in a fashion similar to what would happen in an integrated biorefinery, this rating would be "Similar."
- **Pieces** mean that the system matches a piece or pieces of the final application. For example, if a hybrid poplar farm were producing woodchips for a biomass-fed power plant that took the wood chips and burned them directly, the rating would be "Pieces" since the unit operation reflects a part of what would happen in an integrated biorefinery, although it does not reflect the whole system.
- **Simulated** means that the system reflects a simulated environment in which actual material is used; however, the process is simulated to give the user an idea of what can happen. For example, if a hybrid poplar farm were to produce saw logs, and some of the saw logs were run in a chipper as a controlled experiment to collect data, this process would be rated as "Simulated."
- **Paper** means that the system exists on paper and that there is no hardware system.

For conversion (pyrolysis and gasification) and upgrading (hydrotreating and FT synthesis), the following technology readiness criteria were used:

- **Current production rate** (MT/year). This criterion is justified since this gives an indication of how relevant the process is to a commercial operation.
- **System fidelity**. This criterion is justified since this give an indication as to the degree of integration the process block has with respect to the entire operation.
- **Feed characteristics**. This criterion is justified since this gives an indication as to how realistic the process was demonstrated with regards to feed.
- **GHG reduction**. This criterion is justified as it demonstrates an effort by the technology provider to develop a process that has a positive effect on GHG emissions.

- **Key economic factor – capital expense**. This criterion is justified as it demonstrates the degree to which the process has been engineered and developed to be constructed at a cost such that it can be widely accepted in the marketplace.
- **Key economic factor – operating expense**. This criterion is justified as it demonstrates the degree to which the process has been engineered and developed to be operated at a cost such that it can be widely accepted in the marketplace.
- **Key performance factor – hours**. This criterion is justified as it demonstrates the level of effort that has been spent in developing the process.
- **Key performance factor – percent of data available**. This criterion is justified as it demonstrates the availability of data that should come as a result of the level of effort spent in testing. The two caveats of this criterion are that: (1) the accuracy of the data is not taken into consideration, which, in and of itself, may or may not reflect the state of technology; and (2) it assigns a low value for the state of technology when the technology provider claims the information is confidential, which may or may not reflect the state of technology.

The scoring matrix for conversion and upgrading is shown below in Table 10.

Table 10. Scoring Matrix for Conversion and Upgrading

Score	Scale MT/day	System Fidelity	Feed Characteristics	GHG Reduction (%)	Key Economic Factor Cap EX $/gal/yr	Key Economic Factor OpEx $/MM BTU	Key Performance Factor Hours	Key Performance Factor % Data
9	Full >50	Identical	Full Range	<0	<2	<13.8	>10,000	100
6	Demo 5–50	Similar	Limited Range	0	2–4	13.8–20.68	1,000–10,000	80–100
5	Pilot 0.5–50	Pieces	Relevant		4–8	20.68–34.48	100–1,000	60–80
3	Lab < 0.5	Paper	Simulated	>0	>8 or Confidential	>34.48	1–100 or Confidential	40–60
1	Paper	None	Paper	n/a	n/a	n/a	n/a	<40

Again, by definition, the TRL cannot be higher than nine, nor lower than one. Furthermore, by definition, if the scale of an operation can only be described as a paper study, then the overall TRL cannot be greater than one.

The ranges for scoring the TRLs were developed by evaluating both the range where full scale of the technology is achieved, as well as relevance against the criteria as defined in the DOE document. Since this score is to reflect the state of technology, and not the attractiveness of the technology, it is appropriate to use ranges as a scoring criterion. For example, a technology that is fully developed may not be economically feasible. Hence, is it important to evaluate where a technology is developmentally as well as its feasibility. This scoring is also useful because it can indicate if there is room for improvement, and therefore a smart technology investment.

The scale of operation was based on the fact that most pyrolysis and gasification systems are considered to be at full scale when they are processing 50 MT/day or above. To maintain consistency throughout this exercise, a factor of 10 was used as the appropriate scaling factor between different size plants.[41]

Fidelity is a reflection of the degree of integration in which the conversion or upgrading operation is integrated with the process. The words chosen to describe the degree fidelity were the same words that were in the DOE document. By definition:

- **Identical** means that the system matches the final application in all respects. For example, if a pyrolysis process were directly connected to an upgrading operation for stabilizing bio-oil, this rating would be "Identical."
- **Similar** means that the system matches the final application in almost all respects. For example, if a pyrolysis process were feeding a slip stream to an upgrading process, this rating would be "Similar."
- **Pieces** mean that the system matches a piece or pieces of the final application. For example, if a pyrolysis process had samples taken that were sent to an operation that performs upgrading, the rating would be "Pieces" since the unit operation reflects a part of what would happen in an integrated biorefinery, although it does not reflect the whole system.
- **Simulated** means that the system reflects a simulated environment in which actual material is used, however, the process is simulated to give the user an idea of what can happen. For example, if a pyrolysis process had samples taken and tested in lab studies to characterize the performance, this process would be rated as "Simulated."
- **Paper** means that the system exists on paper and that there is no hardware system.

Feed characteristic is a rating of how similar the feed used in the process was compared to the intended feed. The words chosen to describe the degree fidelity were the same words that were in the DOE document. By definition:

- **Full Range** means that the full range of designated feed is used. For example, in the project scenario, if a pyrolysis process has been demonstrated to work on a full range of hybrid poplars, as well as other related species, this process would be rated at "Full Range."
- **Limited Range** means that a limited range of designated feed is used. For example, in the project scenario, if a pyrolysis process has been demonstrated with one variety of hybrid poplar, or only demonstrated on a closely related feed like aspen or cottonwood, the process would be rated at "Limited Range."
- **Relevant** means that a feed that provides a reasonable analogy to what was designated is used. For example, in the project scenario, if a pyrolysis process has been demonstrated with pine or another soft wood, but not with hybrid poplar, the process would be rated as "Relevant."
- **Simulated** means that a feed that was meant to represent the intended feed in a limited way was used. For example, in the project scenario, if a pyrolysis process has been

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[41] Adapted from PYNE IEA Bioenergy http://www.pyne.co.uk

demonstrated using a mixture of cellulose, hemicelluloses, and lignin to simulate the composition of wood, the process would be rated as "Simulated."

- **Paper** means that the system exists on paper and that there is no hardware for the system.

For GHG reduction, three ratings were developed. Processes either demonstrated:

- GHG reduction compared to a petroleum equivalent.
- GHG emission that is the same as the petroleum equivalent.
- GHG emission that is greater than the petroleum equivalent or no determination has been made or it is confidential.

The use of life cycle assessment for GHG emissions has yielded very inconsistent results and is dependent on the underlying assumptions used for the calculations.[42]

To determine the appropriate score, the team used the following approach:

- Since there was no consensus on the appropriate protocol for performing a life cycle assessment for GHG emissions, it was decided that there was little value in refining the scoring of this criterion.
- It was assumed that the GHG calculation would encompass everything from the growing/harvesting to the production of the final fuel.
- Technology providers who revealed a reduction in GHG emissions received the same score of 9. Likewise, technology providers who revealed an increase in GHG emissions, or if no determination was made or if the information was considered confidential, received the same score of 3.

For the capital expense rating under key economic factors, the rating system was set up using dry mill corn ethanol as a bench mark. As a rule of thumb, $2 is spent for each gallon per year of capacity to build a dry mill corn plant. From that point, it was assumed that each level down would result in a doubling of relative construction costs. Technology providers were asked for the expected capital costs for the block under consideration. In cases where the technology provider claims that the capital costs were confidential, a score of 3 was assigned.

For the operating expense rating under key economic factors, the rating system was set up using $80 dollars per barrel of crude oil as a basis. Assuming that there is 5,800,000 Btu in a barrel of crude oil, the economic value of the energy is $13.8 per million Btu. The other milestones were set at $120/barrel of crude and $200/barrel of crude. For determining the operating expense, technology providers were asked to include the cost of feed, as well as any other inputs for cash flow determination.

Under key performance factors, technology providers were asked to report the number of hours of operating experience that they had with their system. This is the total number of hours that their equipment has been operational at all levels. As a basis, 10,000 hours was chosen since it represented a little over a year of continuous operations. Similar to how other categories were treated, a factor of 10 was used to scale down the scoring of this category.

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[42] Kruse, J. et al., Life Cycle Analysis of Greenhouse Gas Emissions Associated with Starch-Based Ethanol, prepared for American Coalition for Ethanol, December 1, 2008

Under key performance factors, a criterion titled, "% data" was included. This criterion was meant to represent the extent that data was available and to correlate the amount of data that was available to the state of technology. Six performance factors were requested from the technology providers that represented a cross section of data that should be collected as the process is being developed. The score given was based on the percent of data that was available. One caveat with this criterion is that if the data could not be collected, the technology provider would be given a low score. During this project, there were several technology providers who did not respond to the requests for information. With this system, these providers would be assigned a low score, which may not be an accurate representation of their state of technology.

Four examples are presented below showing a sample calculation for TRL.

Example 1: Growing/harvesting
Technology provider: Greenwood Resources
Scale: Produces 10,117 MT/yr – Demo scale, score = 6
Area: Operates on 9,308 hectares (23,000 acres) – Full scale, score = 9
Yield: Produces 15 MT/ha-yr (6.1 MT/acre-yr) – Demo scale, score = 6
Fidelity: Similar – going to different markets that have analogies to biofuel production, score = 6
TRL = (6 + 9 + 6 + 6)/4 = 6.75

Example 2: Conversion
Technology provider: Ensyn
Scale: 100 MT/day – Full scale, score = 9
Fidelity: Identical on feed side, similar on product side, score = (9 + 9)/2 = 9
Feed: Demonstrated on hybrid poplar and others, full range, score = 9
GHG: 70% reduction, score = 9
Key economic factor – capital expense = $1.59/gal/yr, score = 9
Key economic factor – operating expense = $26.51/MM Btu, score = 5
Key performance factor – hours = 20,000+, score = 9
Key performance factor – % Data = 100%, score = 9
TRL = (9 + 9 + 9 + 9 + 9 + 5 + 9 + 9)/8 = 8.5

Example 3: Upgrading
Technology provider: BIOCOUP
Scale: >0.5 MT/day – Lab, score = 3
Fidelity: Identical on feed side, paper on product side = (9 + 3)/2 = 6
Feed: Demonstrated on spruce-derived pyrolysis oil – relevant, score = 5
GHG reduction: n/a, score = 3
Key economic factor – capital expense = n/a, score = 1
Key economic factor – operating expense = n/a, score = 1
Key performance factor – hours = between 1–100, score = 3
Key performance actor – % data < 40%, score = 1
TRL = (3 + 6 + 5 + 3 + 1 + 1 + 3 + 1)/8 = 2.87

Example 4: TRL for Greenwood/Ensyn/BIOCOUP process
Total TRL = (6.75 + 8.5 + 2.87)/3 = 5.96

Since this methodology yields a lower score when information is not available, we developed two additional metrics to try to better understand the result when performance and economic data were not considered. The two metrics will be referred to as “Modified TRL 1” and “Modified TRL 2.” In calculating Modified TRL 1, the scores associated with key performance factors were not considered. Using Example 2 above for Ensyn, we would yield the following calculation:

Example 2a (For Modified TRL 1): Conversion
Technology provider : Ensyn
Scale: 100 MT/day – full scale, score = 9
Fidelity: Identical on feed side, similar on product side, score = (9 + 9)/2 = 9
Feed: Demonstrated on hybrid poplar and others, full range, score = 9
GHG: 70% reduction, score = 9
Key economic factor – capital expense = $1.59/gal/yr, score = 9
Key economic factor – operating expense = $26.51/MM Btu, score = 5
TRL = (9 + 9 + 9 + 9 + 9 + 5)/6 = 8.33

In this case, the actual score was lowered since Ensyn had full performance data. If Ensyn did not have full performance data, the score would have increased as compared to the TRL defined.

In calculating Modified TRL 2, the scores associated with key performance factors and key economic factors were not considered. Again, using the Ensyn example, the team would yield:

Example 2b (Modified TRL 2): Conversion
Technology provider: Ensyn
Scale: 100 MT/day – full scale, score = 9
Fidelity: Identical on feed side, similar on product side, score = (9 + 9)/2 = 9
Feed: Demonstrated on hybrid poplar and others, full range, score = 9
GHG: 70% reduction, score = 9
TRL = (9 + 9 + 9 + 9)/4 = 9.00

Ensyn’s score increased because the bias from the key economic factors was eliminated.

Although performance and economic factors are important elements for determining the state of technology, the lack of data does place a bias that may distort where the technology is truly at. In addition, it is assumed that the data for the performance and economic factors were consistent, which may or may not be the case. The only way to verify a consistent basis is to obtain the model or information that the technology providers used to generate the data. Then, assuming that this can be obtained, assumptions such as cost of energy, labor rates, etc. would have to be applied to make sure that the comparison is consistent.

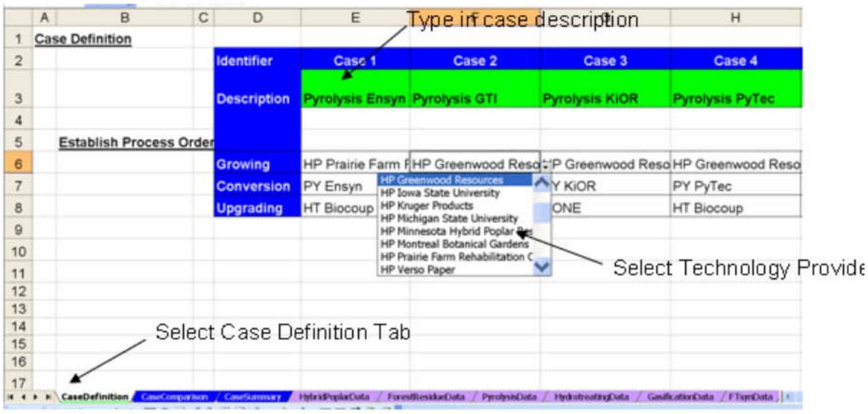
Due to the difficulty in obtaining data, performing a comparison based on all of the criteria established is difficult and may be perceived as unfair. Hence, using a metric such as Modified TRL 2 that uses easier-to-obtain factors may in fact give the best reflection of how the technologies compare to each other, whereas the TRL may best reflect the gaps that have to be filled to advance the technology.

6.3 Subtask 2.3 Results

A spreadsheet-based desktop tool was developed to serve as a quick method for:

- Looking up the TRLs for the different process blocks
- Comparing up to 12 different scenarios for TRLs
- Providing a dashboard to elaborate on a given technology combination, and
- Storing all data for each technology provider.

The methodology developed under subtask 2.2 served as the basis for calculating the TRL in the program. The program uses fields that can be changed easily and can add new technology providers relatively easily. Figure 5 is a screen shot of the case definition tab of the program. This is where the different scenarios are defined using drop-down tabs.



Type in case description

Select Technology Provide

Select Case Definition Tab

1	Case Definition				
2		Identifier	Case 1	Case 2	Case 3	Case 4
3		Description	Pyrolysis Ensyn	Pyrolysis GTI	Pyrolysis KiOR	Pyrolysis PyTec
4						
5	Establish Process Order					
6		Growing	HP Prairie Farm R	HP Greenwood Reso	P Greenwood Reso	HP Greenwood Reso
7		Conversion	PY Ensyn		Y KiOR	PY PyTec
8		Upgrading	HT Biocoup		ONE	HT Biocoup

Figure 5. Case definition tab

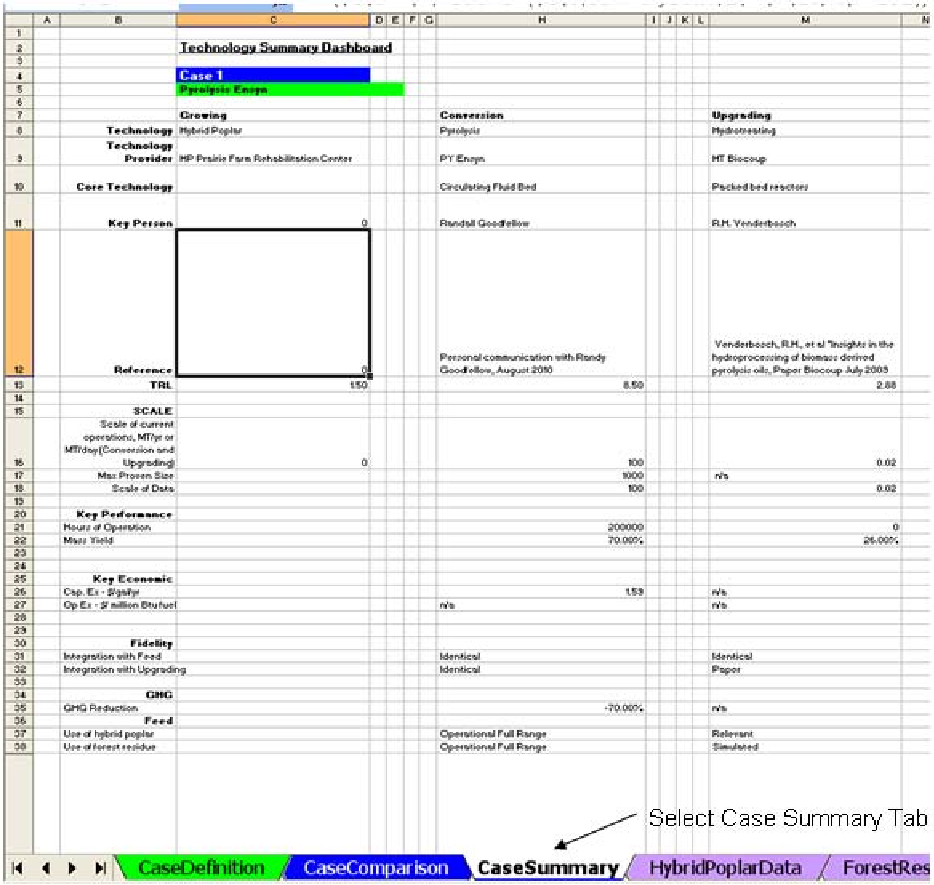
Once the different cases are selected, the case comparison tab will show the TRLs for all scenarios. This is shown in Figure 6.

Select Case Comparison

1	Case Comparison				
2	Case Identifier	Case 1	Case 2	Case 3	Case 4
3	Description	Pyrolysis Ensyn	Pyrolysis GTI	Pyrolysis KiOR	Pyrolysis PyTec
4					
5					
6	Growing	HP Prairie Farm Ret	HP Greenwood F	HP Greenwood F	HP Greenwood F
7	Conversion	PY Ensyn	PY Dynamotive	PY KiOR	PY PyTec
8	Upgrading	HT Biocoup	HT Biocoup	NONE	HT Biocoup
9					
10					
11	**TRL - Growing - Overall**	**1.50**	**6.75**	**6.75**	**6.75**
12	TRL - Growing - Size of Operation	1.00	9.00	9.00	9.00
13	TRL - Growing - Scale of Operation	1.00	6.00	6.00	6.00
14	TRL - Growing - Harvest Yield	1.00	6.00	6.00	6.00
15	TRL - Growing - Fidelity	3.00	6.00	6.00	6.00
16					
17	**TRL - Conversion**	**8.50**	**4.81**	**3.75**	**6.38**
18	TRL - Conversion - Current Scale	9.00	9.00	6.00	6.00
19	TRL - Conversion - System Fidelity	9.00	7.50	7.00	6.00
20	TRL - Conversion - Feed Characteristics	9.00	9.00	5.00	5.00
21	TRL - Conversion - GHG	9.00	3.00	3.00	9.00
22	TRL - Conversion - Key Economic Factors - Cap Ex	9.00	3.00	1.00	6.00
23	TRL - Conversion - Key Economic Factors - Op Ex	5.00	3.00	1.00	1.00
24	TRL - Conversion - Key Performance Factor - Hours of Operation	9.00	3.00	6.00	9.00
25	TRL - Conversion - Key Performance Factor - Data Set Compete	9.00	1.00	1.00	9.00

Figure 6. Case comparison tab

The dashboard for a selected case is shown in Figure 7.



Technology Summary Dashboard

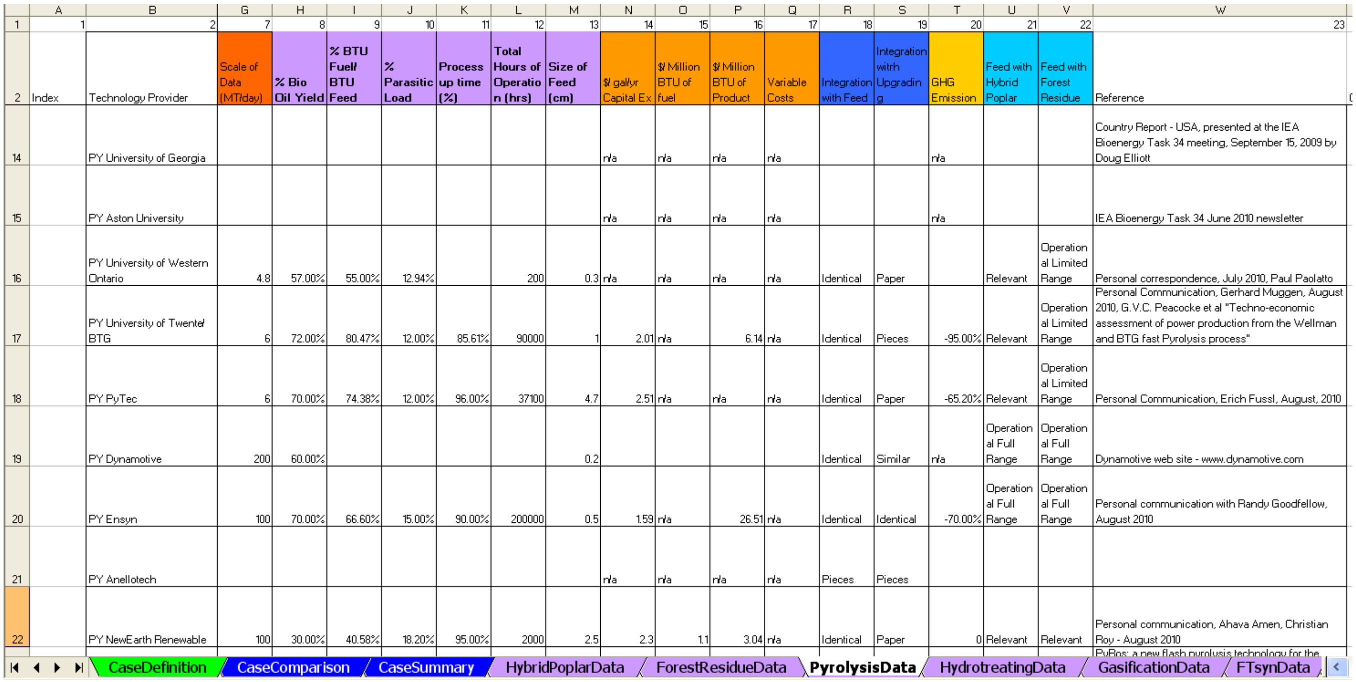
Case 1

Pyrolysis Ensyn

Row	B	C	H	M
7		**Growing**	**Conversion**	**Upgrading**
8	**Technology**	Hybrid Poplar	Pyrolysis	Hydrotreating
9	**Technology Provider**	HP Prairie Farm Rehabilitation Center	PY Ensyn	HT Biocoup
10	**Core Technology**		Circulating Fluid Bed	Packed bed reactors
11	**Key Person**	0	Randall Goodfellow	R.H. Venderbosch
12	**Reference**	0	Personal communication with Randy Goodfellow, August 2010	Venderbosch, R.H., et al "Insights in the hydroprocessing of biomass derived pyrolysis oils, Paper Biocoup July 2009
13	**TRL**	1.50	8.50	2.88
15	**SCALE**			
16	Scale of current operations, MT/yr or MT/day (Conversion and Upgrading)	0	100	0.02
17	Max Proven Size		1000	n/a
18	Scale of Data		100	0.02
20	**Key Performance**			
21	Hours of Operation		200000	0
22	Mass Yield		70.00%	26.00%
25	**Key Economic**			
26	Cap. Ex - $/gal/yr		1.53	n/a
27	Op Ex - $/ million Btu fuel		n/a	n/a
30	**Fidelity**			
31	Integration with Feed		Identical	Identical
32	Integration with Upgrading		Identical	Paper
34	**GHG**			
35	GHG Reduction		-70.00%	n/a
36	**Feed**			
37	Use of hybrid poplar		Operational Full Range	Relevant
38	Use of forest residue		Operational Full Range	Simulated

Figure 7. Case summary tab

Data for the different blocks are stored under the different tabs. As an example, the data matrix for pyrolysis is shown in Figure 8.



	A	B	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W
1	1	2	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
2	Index	Technology Provider	Scale of Data (MT/day)	**% Bio Oil Yield**	**% BTU Fuel/ BTU Feed**	**% Parasitic Load**	**Process up time (%)**	**Total Hours of Operation (hrs)**	**Size of Feed (cm)**	$/ gal/yr Capital Ex	$/ Million BTU of fuel	$/ Million BTU of Product	Variable Costs	Integration with Feed	Integration witrh Upgrading	GHG Emission	Feed with Hybrid Poplar	Feed with Forest Residue	Reference
14		PY University of Georgia								n/a	n/a	n/a	n/a			n/a			Country Report - USA, presented at the IEA Bioenergy Task 34 meeting, September 15, 2009 by Doug Elliott
15		PY Aston University								n/a	n/a	n/a	n/a			n/a			IEA Bioenergy Task 34 June 2010 newsletter
16		PY University of Western Ontario	4.8	57.00%	55.00%	12.94%		200	0.3	n/a	n/a	n/a	n/a	Identical	Paper		Relevant	Operational Limited Range	Personal correspondence, July 2010, Paul Paolatto
17		PY University of Twente/ BTG	6	72.00%	80.47%	12.00%	85.61%	90000	1	2.01	n/a	6.14	n/a	Identical	Pieces	-95.00%	Relevant	Operational Limited Range	Personal Communication, Gerhard Muggen, August 2010, G.V.C. Peacocke et al "Techno-economic assessment of power production from the Wellman and BTG fast Pyrolysis process"
18		PY PyTec	6	70.00%	74.38%	12.00%	96.00%	37100	4.7	2.51	n/a	n/a	n/a	Identical	Paper	-65.20%	Relevant	Operational Limited Range	Personal Communication, Erich Fussl, August, 2010
19		PY Dynamotive	200	60.00%					0.2					Identical	Similar	n/a	Operational Full Range	Operational Full Range	Dynamotive web site - www.dynamotive.com
20		PY Ensyn	100	70.00%	66.60%	15.00%	90.00%	200000	0.5	1.59	n/a	26.51	n/a	Identical	Identical	-70.00%	Operational Full Range	Operational Full Range	Personal communication with Randy Goodfellow, August 2010
21		PY Anellotech								n/a	n/a	n/a	n/a	Pieces	Pieces				
22		PY NewEarth Renewable	100	30.00%	40.58%	18.20%	95.00%	2000	2.5	2.3	1.1	3.04	n/a	Identical	Paper	0	Relevant	Relevant	Personal communication, Ahava Amen, Christian Roy - August 2010
																			PyRos: a new flash pyrolysis technology for the

Figure 8. Pyrolysis data tab

6.4 Subtask 2.4 Results

Using the desktop tool, the team calculated the TRLs for the different technology providers. In Table 12, three forest residue customers are presented as opposed to technology providers. It was decided that demonstrating where the users were was a better depiction of the state of technology as opposed to trying to make a case for the hundreds of different contractors who provide supplies to the users. For pyrolysis, hydrotreating, gasification, and FT synthesis, and for comparative purposes, the scores for the full TRL are shown below. This also displays what happens when (1) the TRL does not include performance factors for the conversion and upgrading blocks (Modified TRL 1); and (2) the TRL does not include the performance and economic factors for the conversion and upgrading blocks (Modified TRL 2).

The rationale for calculating the modified TRLs is to understand the effect of not including the performance and economic criteria into the TRL. As mentioned earlier, a significant challenge in this project was obtaining data for the performance and economic criteria of the TRL. The original model, as it was established, assumed that a lack of performance and economic data is a reflection of the state of technology. Although the team has taken into consideration the issue of confidentiality, the general net result of the lack of performance or economic data, whether confidential or not, results in a bias towards a lower TRL score. These comparisons for the different blocks are shown in Table 11 through Table 16.

Table 11. TRL – Hybrid Poplar

Technology Provider	TRL
Montreal Botanical Gardens	4
Alberta Pacific Forest[43]	3.5
Michigan State University	2.5
Verso Paper*	4.25
Greenwood Resources	6.75
Kruger Products**	2.75
Catalyst Paper**	2.75

* Incomplete data collection
** Plantation closing down

Table 12. TRL – Forest Residue

Forest Residue Customer	TRL
Shasta Energy Company	6.25
Marubeni Sustainable Energy*	4.25
Boralex	7.5

* Incomplete data collection

Table 13. TRL – Pyrolysis

Technology Provider	TRL	Modified TRL 1	Modified TRL 2
University of Western Ontario	4.38	4.00	5.50
Btg	7.50	7.00	6.75
PyTec	6.38	5.50	6.50
Dynamotive*	4.81	5.75	7.13
Ensyn	8.50	8.33	9.00
Anellotech	2.63	2.83	3.75
NewEarth Renewable	7.00	6.83	6.50
ABRI-Tech*	2.63	2.83	3.75
KiOR*	3.75	3.83	5.25
Avello Bioenergy*	2.63	2.83	3.75
RTI International	2.00	2.00	2.50
Gas Technology Institute	6.25	6.50	6.00

*Incomplete data collection

Table 14. TRL – Hydrotreating

Technology Provider	TRL	Modified TRL 1	Modified TRL 2
Pacific Northwest National Laboratory	3.00	3.33	4.50
University of Massachusetts	3.00	3.33	4.50
Mississippi State University	2.81	3.08	4.13
BIOCOUP	2.88	3.17	4.25
Dynamotive	2.88	3.17	4.25
UOP	3.00	3.33	4.50

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[43] Plantation starting up – about 15 years from first harvest

Table 15. TRL – Gasification

Technology Provider	TRL	Modified TRL 1	Modified TRL 2
Choren	5.75	5.33	7.50
Clearfuels	4.00	4.33	6.00
Red Lion	5.63	4.50	6.25
TRI	5.19	4.42	6.13
Stora-Enso	5.69	5.75	8.13
GTI-UPM	5.50	4.33	6.00
CUTEC	4.44	3.42	4.63
TUV	5.56	4.42	6.13
RTI	4.00	3.33	4.50

Table 16. TRL – Fischer-Tropsch Synthesis

Technology Provider	TRL	Modified TRL 1	Modified TRL 2
Choren	4.88	4.50	5.75
RenTech	4.38	4.00	5.00
Velocys	4.94	4.25	3.63
Pacific Renewable Fuels	3.38	2.83	3.75
Emerging Fuels Technology	4.69	3.75	4.63
Stora Enso	4.50	4.67	6.50
GTI-UPM	2.38	1.50	1.75
CUTEC	4.06	3.08	3.63
TUV	4.94	4.08	5.13
RTI	2.63	1.83	2.25

The comparison of the TRL and the Modified TRLs shows that the exclusion of the performance and economic data did not always result in a higher score. However, it does normalize the comparison between the different technologies as it allowed us to compare the different technologies against data that was available.

7 Conclusions

Although there have been significant advances in the technology associated with the two pathways that were investigated in this report, significant hurdles remain that must be overcome in order to recognize widespread use of these technologies. Specifically:

- Although the use of forest residue is being demonstrated at a commercial level, its widespread use is very dependent on the opportunity relative to the terrain as well as the forestry practice. Although technology is being developed to help improve the cost of harvesting forest residue, the different scenarios that exist require addressing each opportunity on a case-by-case basis.
- Hybrid poplar needs to overcome the issue of disease resistance and the ability to be harvested multiple times.
- Pyrolysis technology needs to be able to produce a material that is easily stabilized and upgraded. Recent work in catalytic pyrolysis appears promising in delivering a material that is not only stable but can be incorporated into existing infrastructure.
- The integration of gasification and FT technology is starting to reach the demonstration scale and is scheduled to be in operation within a year. Results from these demonstrations will show the technology's full capability.

To be fully effective in obtaining accurate state-of-technology assessments, there is a need to obtain information at a higher level of fidelity than what was obtained in this investigation. Due to resource and confidentiality issues, gathering information at this level was difficult. In addition, if the information used in the recent DOE funding opportunity had been made available, this process would have been much simpler.

In the future, achieving a different way of understanding the state of technology might be helpful. For example, workshops could be held that allow technology providers to express resource requirements and fill technology as well as tie workshop participation to eligibility for future DOE funding. Also, through these workshops, consensus could be gained on methods for calculating TRLs as well as assumptions used in the calculations to provide the consistency necessary for future work in this area.

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This report discusses an investigation that addressed two thermochemical conversion pathways for the production of liquid fuels and addressed the steps to the process, the technology providers, a method for determining the state of technology and a tool to continuously assess the state of technology. This report summarizes the findings of the investigation as well as recommendations for improvements for future studies.

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