Comparative analysis and benchmarking of commercial and emerging fast pyrolysis technologies

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ABSTRACT: It is well established that producing sustainable fuels and replacing the fossil-based ones is one of the key solutions to achieving net-zero emissions goals. One of the most advanced commercial-scale pathways to biofuels available today is fast pyrolysis. However, due to the need for a supportive regulatory environment and mitigation strategies for uncertainties related to costs and feedstock quality, fast pyrolysis is not yet being widely implemented.

In this case study, three fast pyrolysis technologies with a technology readiness level (TRL) of 6 and above have been compared to distinguish between them and identify the conditions under which they are economically viable. The circulating fluidized bed (CFB), rotating cone (RC), and mechanically assisted fluidized bed (MFB) fast pyrolysis technologies were considered. First, the flow diagram and a mass and energy balance comparison were addressed. It was revealed that the RC configuration has better bio-oil yields because it can handle smaller particles. The MFB configuration has a progressive condensation unit at the end of the process, which produces a nearly dry oil having a higher energy content.

Four implementation scenarios were studied. The first was the fast pyrolysis standalone process, where all options had marginal economic attractiveness, and the RC configuration economically outperformed the other two. Integration of a fast pyrolysis plant into a sawmill in the second scenario was found to bring significant improvements in revenues and internal rate of return (IRR). Realization of the full value of bio-oil (the third scenario) brought significantly more revenues for the MFB. Finally, the fourth scenario involved adding a progressive condensation unit, which increased the capital expenditure (CAPEX) by 3%–4% while increasing revenues by 32%–35%. A sensitivity analysis highlighted the importance of financial support towards capital cost and the full valuation of bio-oil for the economic viability of fast pyrolysis processes. Progressive condensation leading to more added-value bio-oil makes the standalone fast pyrolysis process more profitable.

Application: Distinguishing between different configurations of fast pyrolysis technologies and identifying the conditions under which the technology is economically viable is essential for incorporating the most appropriate and sustainable pyrolysis strategy among the ones currently available.

Today's forest products industry is decarbonizing and increasingly seeks to achieve net-zero greenhouse gas (GHG) emissions by 2050. This will require sustainable biorefinery technology pathways deployed at large scale within the coming years. To choose the best technologies, triaging at the early design stage can be complex for many reasons, especially considering that biorefinery technologies are at different levels of readiness and that cost estimates, as well as risks, are difficult to systematically and accurately assess.

In recent years, most of the fast pyrolysis technologies have been implemented at pre-commercial scale, with goals of implementing large-scale commercial units by 2030. For example, the Canadian company Vyterra (Ensyn; Ottawa, ON, Canada) has had a 100 metric tons/day plant in Ontario operating for many years, and more recently has installed 2 parallel lines of the same capacity in Québec [1]. At the same time, the next generation of fast pyrolysis processes is being developed considering, for example, integration of progressive condensation of the pyrolysis vapors to intensify the pyrolysis process and full recovery of biochar, as well as rethinking the design to establish a modular off-the-shelf pyrolysis system. An example of this next generation pyrolysis technology is the process being developed at Iowa State University (ISU), where a novel "autothermal" pyrolysis reactor includes a progressive condensation of pyrolysis vapors for the production of value-added products [2]. Iowa State University is developing their modularized and process intensified approach at the RAPID (Rapid Advancement in Process Intensification Deployment) Institute [3].

However, fast pyrolysis has not found widespread application as quickly as expected, due mainly to marginal economics and the need for an updated, ambitious, and robust regulatory environment (e.g., mandatory renewable

content in fuels, capital cost support, carbon credits, incentives for biofuels, etc.). Feedstock quality and costs are also critical to the economic viability of the fast pyrolysis technologies. With volatile oil prices, uncertainties in climate policy and related instruments, and competitive access to biomass, the return on investment (ROI) for fast pyrolysis is often unattractive.

On the other hand, fast pyrolysis process implementation in an industrial symbiosis context, as when integrated with existing mills (e.g., sawmills, pulp mills, etc.), for example, can potentially lower feedstock transportation costs and/or generate higher revenues for the host site. Implementing a fast pyrolysis plant alongside an existing mill is attractive because forest residuals (slash) and/or sawmill residues can be used as feedstock, energy integration is possible for feedstock drying, and in some cases, the pyrolysis oil can be used on the host site to displace fossil fuels and reduce GHG emissions accordingly.

In recent years, the development of fast pyrolysis technologies has resulted in diverse variants in process configuration. These variants incorporate a difference in the core of the reactor operation and/or the bio-oil production and purification method. Some of these technologies have made progress in recent years and have reached a technology readiness level (TRL) of 6 and beyond. In this work, three technologies with TRLs of 6 and beyond are compared from technical and economic perspectives. Distinguishing between different configurations of fast pyrolysis technologies, as well as identifying the conditions under which the technology is economically viable, is essential to incorporating the most appropriate and sustainable pyrolysis strategy.

LITERATURE REVIEW

Fast pyrolysis: science and different modes of pyrolysis

To effectively distinguish between the fast pyrolysis technologies used for this case study, certain fundamentals of fast pyrolysis are reviewed.

The pyrolysis process has existed for decades; however, it has been developed to maximize production of liquids only in the last 40 or so years. Fast pyrolysis (FP) is a thermochemical conversion process, in the near absence of oxygen, that can liquefy solid biomass into liquid bio-oil, with a high potential for energy applications as well as value-added bioproducts. Fast pyrolysis operates at a temperature of around 500°C, a short vapor residence time (typically less than 2 s vs. 5 s to hours for other modes of pyrolysis), and a short solids residence time (typically under 10 s).

According to Bridgewater [4], five important characteristics should be considered for the fast pyrolysis process:

1. **Feed moisture of less than 10%:** A higher moisture content lowers the product heating value and can lead to phase separation.
2. **High heating rates and high heat-transfer rates with finely ground biomass (less than 3 mm):** The small particle diameter increases biomass surface area and heat transfer rates.
3. **Controlled temperature of about 500°C and a short vapor residence time of less than 2 s:** Various methods can be used to provide the required heat to stabilize the reactor temperature [5]:
   - Hot walls or hot tubes in the reactor
   - Hot fluidizing gas

Property	Typical Value	Range
Moisture content	25%	15%–35%
Density	1.2 kg/L	-
Elemental analysis	C: 57% H: 6% O: 37% N: trace Ash: trace	C: 55–60% H: 5.5–7% O: 35–40% N: 0–0.2% Ash: 0-0.2%
HHV (depends on water)	18 MJ/kg	16–19 MJ/kg
Appearance		Dark brown flowing liquid (depends on the feedstock and the mode of fast pyrolysis).
Odor		Acrid smoky smell due to presence of aldehydes and acids.
Miscibility		Single-phase mixture with 15% to 35% water. Immiscible with petroleum-derived fuels, but miscible with polar solvents.

C = carbon; H = hydrogen; O = oxygen; N = nitrogen; HHV = higher heating value.

I. Properties of crude bio-oil obtained with fast pyrolysis process [7,8].

- Use of recycled hot sand (heated separately)
- Controlled addition of oxygen to permit in situ heat generation (so-called "auto-thermal" operation)

4. **Rapid removal of the biochar produced to minimize cracking of hot vapors.**
5. **Rapid cooling of the pyrolysis vapors to produce bio-oil.**

Typical yields for fast pyrolysis are [4,6]:
- Liquid (bio-oil and water): 60 wt%–75 wt%
- Biochar: 15 wt%–25 wt%
- Non-condensable gases: 10 wt%–20 wt%

Table I summarizes the main properties of crude bio-oil. There is a significantly wide range of values, which is mainly due to the process configuration, including the reactor as well as downstream processing.

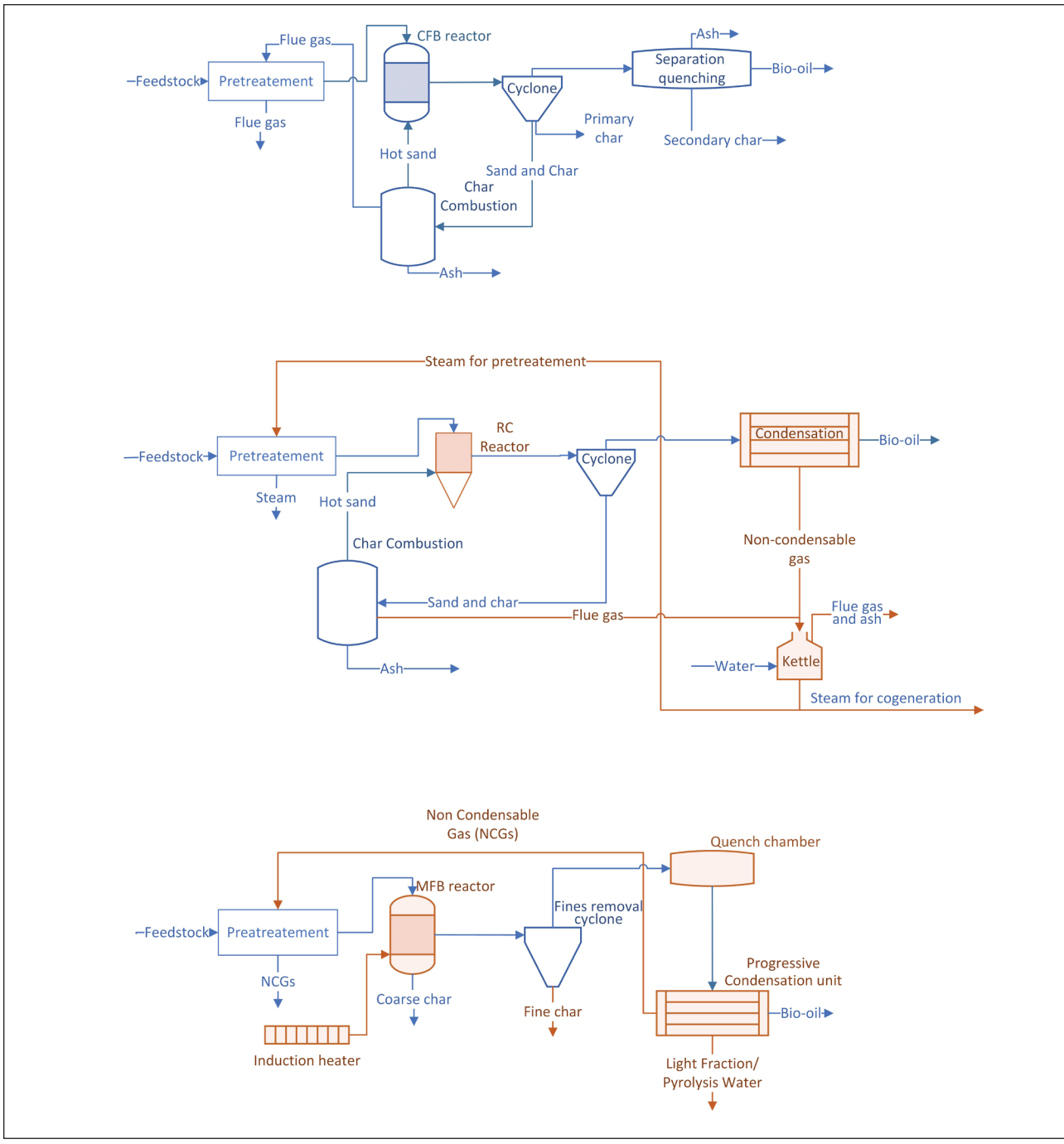
As discussed previously, these technologies have been further developed to bring them up to TRLs of 6 or beyond, such as circulating fluidized bed (CFB), bubble fluidized bed (BFB), rotating cone (RC), vacuum, ablative vortex, mechanically-assisted fluidized bed (MFB), the auger reactor, or microwave pyrolysis. **Table II** presents the key characteristics of these technologies.

The current trends in fast pyrolysis technologies are changing the historical process paradigm by considering value-added liquids, value-added biochar, or modularization. Some examples of current trends in fast pyrolysis are listed below:

- BTG Bioliquids (BTG-BTL; Enschede, Netherlands) and TechnipFMC (London, UK) completed construction of a fast pyrolysis plant in January 2022 to convert sawmill residues in Gävle, Sweden. The plant will have a production capacity of 24,000 metric tons of bio-oil

Fast Pyrolysis Technology	Particle Size, mm	Residence Time, s	Bio-oil Yield (on dry feed)	Features	References
Circulating fluidized bed (CFB)	1–2	0.5–1	60%–70%	- Suitable for high throughput - Higher gas velocities - Improved heat transfer between biomass particles and bed material	[7,9,10]
Bubble fluidized bed (BFB)	Less than 2–3	2–3	70%–75%	- Good temperature control - Easy scaling - Residence time of solid and vapors controlled by fluidizing gas flow rate	[7,9,10]
Rotating cone (RC)	0.2 µm–2 cm	1	50%–70%	- Centrifugation used to drive hot sand and biomass - Less carrier gas requirement for the reactor	[7,11,12]
Vacuum	2–5 cm		30%–45%	- Less biochar in the liquid product due to lower gas velocities - No requirement for carrier gas - Mechanically complicated	[7,9,13]
Ablative vortex	Up to 20	50–100 ms	60%–65%	- Processing equipment is small because there is no inert gas - Limited by heat supply to reactor	[7,9]
Mechanically-assisted fluidized bed (MFB)	4–8	0.7–1.7	40%–60%	- Mechanically mixed - No fluidization gas used - Good mixing between the injected biomass and the bed material	[14,15]
Auger/screw reactor	Up to 20	5–30	30%–50%	- Does not require carrier gas - Lower process temperatures (400°C) - Rapid heating biomass if granular heat carriers used	[10,16-18]
Microwave	2–6	10-25 min	20%–40% (depending on temperature)	- Heating happens by the interaction of biomass with the electric element of the electromagnetic wave - Large particles can be used without the need for an energy-intensive pre-treatment to reduce particle size	[19-21]

II. Fast pyrolysis technologies and features.

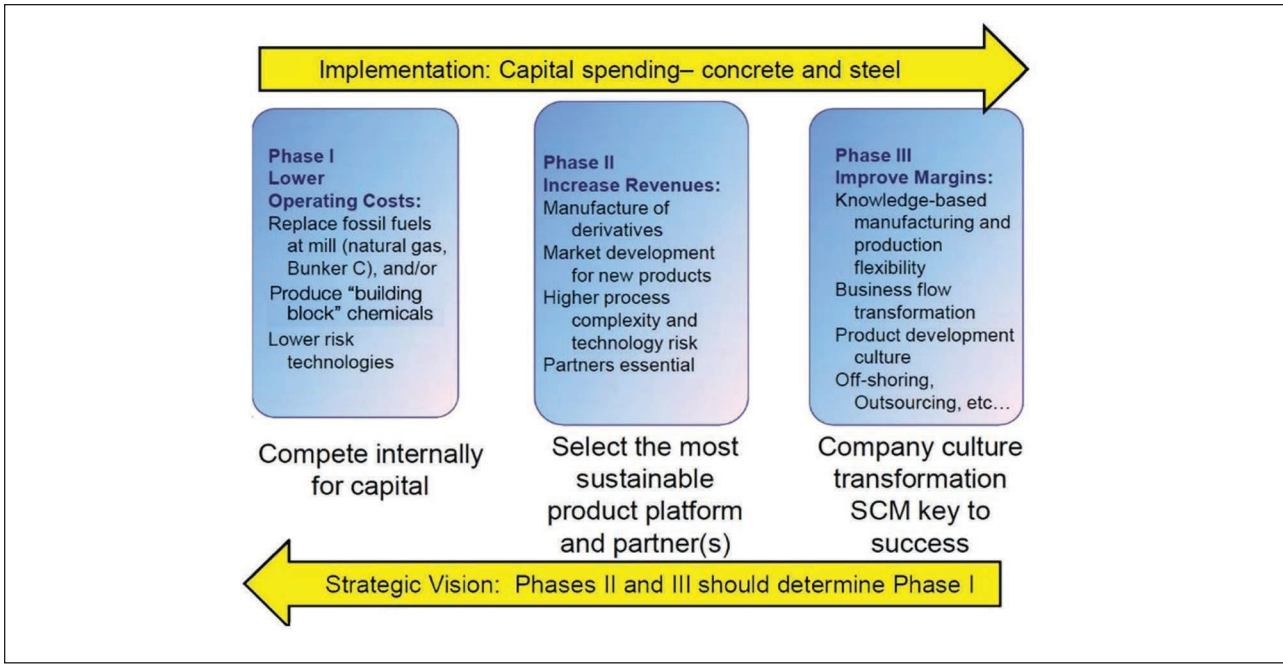


1. Flow diagram of three technology configurations. From top to bottom: circulating fluidized bed (CFB), rotating cone (RC), and mechanically assisted fluidized bed (MFB).

per year with the RC fast pyrolysis technology developed by BTG-BTL [22].

- In 2016, Vyterra licensed CFB pyrolysis technology in Port-Cartier, QC, Canada, to produce 40 million L/year from 65000 dry metric tons/year of cellulosic woody biomass [23].
- Bio-TechFar (Toronto, ON, Canada) has more recently developed a new, mechanically fluidized reactor that has four byproducts: pyrolysis oil and an aqueous fraction through progressive condensation, biochar, and pyrolysis gas [24].

For this study, three fast pyrolysis technologies are reviewed and systematically compared: CFB, RC, and MFB. Understanding the specific designs of these technologies and exploring the relative conditions under which each would be economically viable are an important part of this study.



2. Phased implementation approach [26] (SCM = supply chain management).

Figure 1 shows the simplified process flow diagrams of the three selected fast pyrolysis technologies, which are different from pyrolysis reactor design and configuration perspectives:

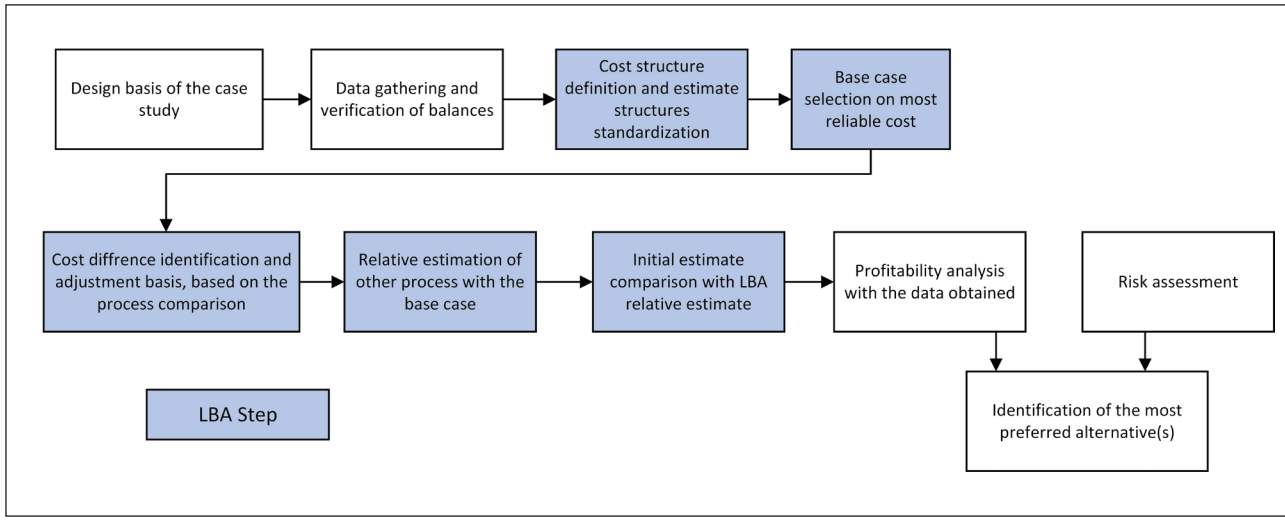
- **CFB:**
  - Fluidized bed using sand as a heat carrier.
  - Flue gas used to dry the biomass.
  - Two types of biochar (primary and secondary) as value-added products.
- **MFB:**
  - No use of sand (and no fluidizing gas).
  - Residence time controlled by the vapor production rate.
  - Purified biochar (not contaminated with sand) as a value-added product.
- **RC:**
  - Good flexibility with regard to incoming material, good biomass yield, and ability to process small particles.
  - Residence time fixed by rotation speed.
  - Flue gas used to produce steam.

Fast pyrolysis: implementation risks

The implementation of these configurations at commercial scale faces unique risks related to market, technology, financial, regulatory, and supply chain. Each of these risk categories requires effective mitigation strategies that should be considered in the early stages of biorefinery process design. One way to have insight into which parameters are the most critical is to perform a sensitivity analysis, and where appropriate, consider mitigation strategies that should be applied — possibly considering a phased implementation approach [25]. The lowest-risk technology option is considered as the "base case" so that variants of the base case can be considered on a risk-return basis.

Figure 2 summarizes the phased implementation approach for addressing technology and market risks in conjunction with business transformation and related risk mitigation strategies, as presented by Clerc et al. [26], considering three generic phases. To ensure that a biorefinery process/technology is implemented with mitigated risk, a strategic vision based on long- and short-term goals and a diversified portfolio of value-added products must be established. The last phases should determine the first one, where the main goal is to lower operating costs while increasing revenues by developing new products. Market opportunities and partnership potential must be assessed, as well as supply chain management.

At the early design stage, it is essential to estimate relative capital costs, operating costs, and revenues for different process options being considered. A techno-economic framework based on the TRL and on the information available was developed by Buchner et al. [27]. It implies that different estimation methods should be used, depending on the level of maturity of the technology studied, which is not an adequate mode of comparison when using different technologies. Trottier et al. [28] present a systematic methodology for estimating relative capital and operating costs at the early design stage called large block analysis (LBA), initially introduced by Hytönen and Stuart [29]. The refined methodology of Trottier et al. can be adapted to address process risks while developing the capital and operating costs on a comparable basis. **Figure 3** summarizes the LBA approach used in this study. A key element of this methodology is that once the initial estimate basis has been



3. Adapted large block analysis (LBA) approach [28].

obtained, it is necessary to define a cost structure by selecting the most detailed option and to estimate individual cost elements on the same basis (considering fundamental differences as well as year and capacity). Once this step has been completed, the most reliable cost is used as the basis to identify the differences between the base case and the other technologies considered.

With reliable estimates for capital and operating costs, it is possible to balance risk with return on investment. Birkhofer [30] developed four principles of risk-driven design. After identifying uncertainties regarding design risks, the second principle is about making risk-driven decisions. A balance between higher-risk, higher-return options and lower-risk, lower-return options needs to be established. At an early design stage, there are numerous risks regarding scale-up, yields, operating costs, future improvements in costs as the technology matures, and feedstock availability and cost [31]. Risks linked to the phased implementation, capital and operating cost estimates, economic viability, and balancing risk with return requires a systematic assessment and good engineering judgement that is consistent with scientific and engineering principals and available technical and commercial information.

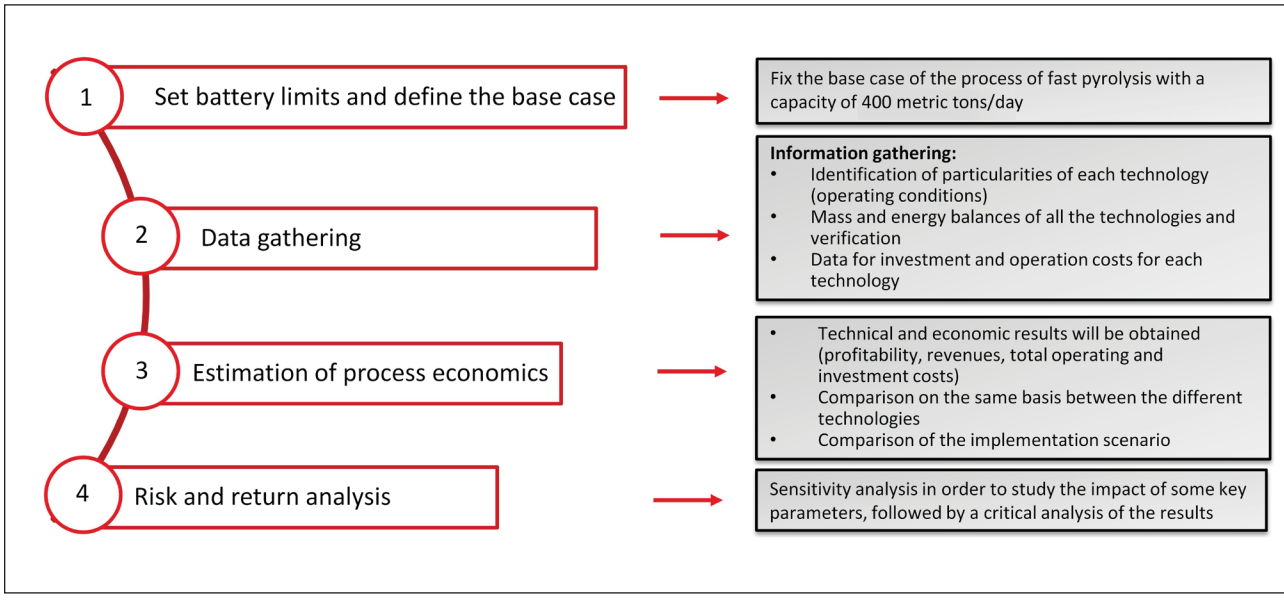
For this study, the goals were (1) to determine the conditions for economic viability of three technologies: a conventional fast pyrolysis process and two emerging intensified fast pyrolysis processes leading to value-added products, considering a phased approach for risk mitigation; and (2) to elucidate the relative strengths and weaknesses of four fast pyrolysis implementation scenarios.

PROPOSED METHODOLOGY FOR FAST PYROLYSIS TECHNOLOGY ASSESSMENT

The methodology presented in **Fig. 4** summarizes the four steps used to perform the systematic comparative analysis and benchmarking of the three fast pyrolysis technologies.

Implementation Scenario	Products	Phase 1 (0-2 years)	Phase 2 (3-25 years)	Revenue Diversification
1. Fast pyrolysis standalone	Crude bio-oil Biochar	Fast pyrolysis (400 metric tons/day)		- Bio-oil sold in Canada - Biochar sold as agricultural fertilizer
2. Fast pyrolysis integrated with a sawmill	Crude bio-oil Biochar Lumber	Sawmill (850 metric tons/day)	+ Fast pyrolysis (400 metric tons/day)	- Bio-oil sold in Canada - Biochar sold as agricultural fertilizer
3. Fast pyrolysis integrated with a sawmill + full valuation of bio-oil	Crude bio-oil Biochar Lumber	Sawmill (850 metric tons/day)	+ Fast pyrolysis (400 metric tons/day)	- Incentives for bio-oil in the United States - Biochar sold as agricultural fertilizer
4. Fast pyrolysis + progressive condensation unit	Upgraded bio-oil, Biochar	Fast pyrolysis (400 metric tons/day) + installation of progressive condensation unit		- Bio-oil sold as a value-added product - Biochar sold as agricultural fertilizer

III. Implementation scenarios and phased approach for the case study.



4. Methodology followed for the case study.

Once the project battery limits were defined in the first step, it was essential to define the necessary technical performance and economic attributes of the technologies. The third step is crucial because of the need to clarify the differences in technology at a macroscopic level by identifying first the expected differences between the technologies, and then assessing how to realistically reflect these in the economic estimates. The techno-economic results were confirmed using the I-BIOREF decision-making tool, developed by CanmetENERGY of Natural Resources Canada [32]. The I-BIOREF software can be used for modeling and analysis to perform technical, economical, environmental, and socio-economic assessment of implementation biorefinery processes either in an existing industrial host site (e.g., pulp mills, sawmills, etc.) or on a standalone basis.

Industrial case study

Table III summarizes the implementation scenarios considered for fast pyrolysis. The four implementation scenarios were evaluated for each of the three chosen fast pyrolysis technologies introduced previously, and they were defined in order to consider the symbiotic integration of biorefinery process and various elements of the regulatory ecosystem, including government support, incentives for bio-oil, or carbon credits.

The first scenario focuses on a standalone fast pyrolysis process. The second implementation scenario is related to an integration of fast pyrolysis within an existing sawmill to examine the opportunity of using sawmill residues as feedstock. For this second scenario, the operating expenses (OPEX) of the sawmill was added to the operating cost associated with the fast pyrolysis plant, and the revenues included selling biochar and bio-oil, along with the lumber produced at the sawmill.

The regulatory environment is critical to economic viability for fast pyrolysis and other biofuel processes, especially with regard to incentives/carbon credits eligibility for bio-oil. For this case study, renewable identification numbers (RINs) will be considered as incentives for bio-oil in the implementation scenario 3, where the assumption of selling bio-oil in the United States will be made. The RINs are credits linked to the Renewable Fuel Standard Program of the United States [33].

For the fourth implementation scenario, progressive condensation was added to the fast pyrolysis configurations. Such units improve the quality of bio-oil, which contributes to a higher selling price. Dry bio-oil has a higher energy content and produces a purer, more stable, and more efficient oil. As shown in the block flow diagram in Fig. 1, the MFB technology also includes a progressive condensation unit. The same unit will be added to the CFB and RC technologies to study its impact on the profitability of selling bio-oil at an upgraded price.

Assumptions

Table IV summarizes the assumptions used in the techno-economic assessment, as well as for the operating and capital costs. **Table V** provides the product pricing.

Table VI indicates the assumed operating conditions. The reactor temperature and retention time were chosen as a function of the overall temperature of the fast pyrolysis process, knowing that all three reactors can operate at about this temperature. Forest residues at 50% moisture were chosen as process feedstock and dried to reach 10% moisture at the reactor inlet.

Table VII presents an overview of the assumed yields of the three fast pyrolysis products, which are bio-oil, biochar, and non-condensable gases (NCGs). In general, as was seen in Fig. 1, the NCGs are used for drying in the CFB and MFB processes and for burning RC to obtain steam for gen-

Parameters	Value	Justification
Assumptions for the techno-economic analysis		
Average operating time	7600 h	First two years' operating time will be lower, after which full-time operation will be reached
Project lifetime	25 years	2 years for construction, 23 for operations
Debt	0%	All equity available
Equipment depreciation	50%/ 25%/ 25%	Nominal 3-year accelerated depreciation
Government support for capital costs	40%	Federal and provincial granting programs
Income tax rate	30%	Nominal tax rate
Capital and operating cost assumptions		
Biomass cost	$70/b.d. metric ton	Chipped biomass delivered to mill gate
Water purchase cost	$0.79/$m^3$	
Electricity purchase cost	$8/MWh	Typical value from $5–15/MWh
Sand cost	$200/ton	Delivered price

IV. Case study assumptions.

Product	Product Substituted	Price	Justification
Pyrolysis oil	HFO sold locally	$330/metric ton	$70/barrel /long-term estimate [34]
Pyrolysis oil	HFO sold in U.S.	$330/metric ton $0.66/L	Sale of biofuel on the U.S. market. Most probable D3 RINs value in 2020 [35]
Pyrolysis oil	Upgraded bio-oil (based on HFO)	$1.3/L	HFO average price in 2021 [36]. Price of upgraded oil will be adjusted for each technology by the LHV ratio of HFO and pyrolysis oil.
Biochar	Agricultural fertilizer	$200/metric ton	For lowest risk application as soil amendment
Carbon credits	CO_2	$50/metric ton $CO_{2\text{-eq}}$	Conservative carbon price [37]
Lumber	-	$630/metric ton	Average price on the market for the last five years [38]
Steam	Steam for cogeneration	$49/metric ton	Average price of producing HP steam

V. Product basis pricing (HFO = heavy fuel oil; RINs = renewable identification numbers; CO_2 = carbon dioxide; LHV = lower heating value; HP = high pressure).

Assumed Operating Condition		References & Comments
Reactor temperature	500°C	[4]
Residence time	<2 s	[4]
Biomass feed	Forest residues	Engineering judgment
Moisture at the reactor inlet, %	10	[39]
Moisture in the biomass, %	50	Overall moisture of biomass
Biomass input (dry basis), metric tons/day	400	Base case definition
Biomass input (wet basis), metric tons/day	800	

VI. Assumed operating conditions for the three fast pyrolysis technologies.

	CFB	RC	MFB	Comments & References
Feedstock carbon content, %	60			Typical value for forest residue [40]
Product content				
Bio-oil carbon content, %	56	60	56	[4,40]
Biochar carbon content, %	34	20	35	[41]
NCG carbon content, %	12	22	12	[40]
Bio-oil carbon yield, %	60			[40]
Biochar carbon yield, %	100			Assumption made that biochar is composed of only carbon
NCG carbon yield, %	15			

CFB = circulating fluidized bed; RC = rotating cone; MFB = mechanically-assisted fluidized bed; NCG = noncondensable gas.

VII. Assumed fast pyrolysis products and their properties and yields.

eration. The various yields are based on literature values. The RC reactor has a better bio-oil carbon content because it can handle smaller particles better than the other two types of reactors, as shown in Table II. Furthermore, this reactor produces less biochar, which is why the carbon content is lower than in the CFB or MFB reactors.

RESULTS AND DISCUSSION

Technical analysis

The presentation of the case study results is segregated into two parts. First, the technical analysis with mass and energy balance are presented, followed by an economic analysis including capital and operating costs, as well as the key performance indicators (KPIs).

Table VIII shows the results for the mass balance inputs and outputs at the reactor exit and at the process exit. The two types of outputs were differentiated because the RC and CFB configurations do not have the same outputs at the end of the process as the MFB. In RC, all the biochar going out of the reactor is assumed to be burned to produce steam in a boiler; in CFB, half the biochar will be burned to produce flue gas to dry biomass. The particularity of the MFB process is that the bio-oil will be almost completely dry at the end of the process, due to the progressive condensation unit.

The energy balance inputs and outputs are also presented. According to these results, the MFB process has a higher energy demand, mainly because the reactor is heated by an induction heater.

Economic analysis

The techno-economic results were obtained using LBA methodology presented earlier. The RC technology was considered as the base case having the most reliable cost, and other technologies were estimated independently based on this. In Appendix A, Tables A1 and A2 show the detailed capital and operating cost obtained after the LBA was applied for the four implementation scenarios and the three technologies. The estimates should not be considered as absolute values, but rather values relative one to another.

To compare the profitability and economic viability of the fast pyrolysis technologies in the context of the four implementation scenarios, some KPIs were chosen. They are presented in Appendix B, Table B1.

Table IX gives the results of the first implementation scenario. The incomes presented in the table correspond to the sales of bio-oil, biochar, and steam for cogeneration for one year.

The RC technology has more bio-oil at the end of the process compared to the two other technologies and does not produce any biochar to sell, but it produces steam for cogeneration, which represents $8 M of total revenue. This explains why the RC technology provides the most revenue. In CFB, half the biochar is burned to produce flue gas for drying the feedstock. The other half is sold as biochar, which explains the observation that this technology has the smallest income. The MFB has a slightly higher revenue than CFB, because unlike the CFB technology, all the biochar produced is sold as biochar.

The internal rate of return (IRR) for RC is greater than the other options for this implementation scenario, and it is the technology with the smallest capital investment. More revenues are associated with MFB, which mitigates the impact of having a high capital expenditure (CAPEX).

Earnings before interest, taxes, depreciation, and amortization (EBITDA) is highest for RC because it has the highest revenues, which is also reflected in the EBITDA margin, and the payback period is the shortest. Even if the IRR is similar for the CFB and MFB, the EBITDA is higher for the MFB, as the revenues are larger as well. It is important to mention that MFB offers a diversified product portfolio compared to CFB because it has three products and likely a more robust business model because of this.

Results of implementation scenario 2 where fast pyrol-

	CFB	RC	MFB	Comments
Mass Balance/Inputs				
Biomass, b.d. metric tons/day	400			As presented in the assumption tables
Moisture, b.d. metric tons/day	400			
Carbon in biomass, b.d. metric tons/day	240			
Mass Balance/Outputs at the Reactor Exit				
Pyrolysis oil (b.d. metric tons/day) / Overall yield (%)	264/66	288/70	264/66	Quantity of oil obtained with the assumption made in Table VII presents an overview of the assumed yields of the three fast pyrolysis products, which are bio-oil, biochar, and NCGs. In general, as was seen in Fig. 1, the NCGs are used for drying in the CFB and MFB processes and for burning RC to obtain steam for generation. The various yields are based on literature values. The RC reactor has a better bio-oil carbon content because it can handle smaller particles better than the other two types of reactors, as shown in Table II. Furthermore, this reactor produces less biochar, which is why the carbon content is lower than in the CFB or MFB reactors.
Moisture, %	22			10% moisture at the reactor inlet + 12% of water produced by the reactions
Pyrolysis biochsar (b.d. metric tons/day)/Yield (%)	82/20	48/12	82/20	Results obtained with the assumed yields in the preceding tables.
Pyrolysis gas (b.d. metric tons/day)/Yield (%)	54/14	64/16	54/14	
Mass Balance/Outputs at the Exit of the Fast Pyrolysis Unit				
Bio-oil (b.d. metric tons/day) / Yield dry basis (%)	216/54	232/58	216/54	**MFB**: Pyrolysis oil will be nearly completely dry at the end of the process. **CFB and RC**: Pyrolysis oil will have 22% moisture.
Pyrolysis biochar, b.d. metric tons/day	41	-	82	**CFB:** 50% of the biochar produced by the reactor goes to combustion to produce flue gas for pre-treatment **RC:** All the biochar goes to combustion to produce flue gas for the boiler. **MFB:** All the biochar will be valued as biochar.
Steam, metric tons/day	-	516	-	Steam produced by burning of biochar
Energy Balance/Inputs				
Heat energy, GJ/day	-	-	(1519)	Some of the bio-oil energy will be recirculated to be used for heat energy.
Biomass, GJ/day	7053 (7600–547)	7600	7600	**CFB:** Some energy will be released because 7% of biomass is lost after pre-treatment (547 GJ), which means that the biomass entering in the reactor will bring less energy.
Electrical energy, GJ/day	913	132	308	**CFB:** Electrical energy calculated with I-BIOREF, where a waste treatment unit is considered with the fast pyrolysis plant, which explains the higher need in electricity.
Steam, GJ/day	3	(19)	-	**RC:** Steam needed for the process will be provided by the boiler.
Water, GJ/day	5	15	-	
Total energy needed, GJ/day	7974	7747	7908	

VIII. Summary of overall mass and energy balances for the three technologies.

	CFB	RC	MFB	Comments
Energy Balance/Outputs				
Flue gas, GJ/day	-	482	-	
Bio-oil, GJ/day	4120	4074	3729 (5248–1519)	**MFB:** Energy in the bio-oil will recirculate to be used for heat energy in the input.
Steam, GJ/day	-	1598 (1617–19)	-	Steam needed for the process in the inputs will be provided by the boiler.
Bio-biochar, GJ/day	800	-	1600	**MFB:** More energy is associated with the biochar than in CFB because there is more biochar going out of the process.
Unaccounted-for losses, GJ/day	2954	1076	1757	No specific use for the unaccounted losses
Heat rejected, GJ/day		517	821	
Total Energy Out of the Process, GJ/day	7974	7747	7908	Input energy needed equals the output energy.

CFB = circulating fluidized bed; RC = rotating cone; MFB = mechanically-assisted fluidized bed; NCG = noncondesable gas.

VIII. Summary of overall mass and energy balances for the three technologies - continued.

	Base Line Process FP-400: CFB	FP-400: RC	FP-400: MFB
CAPEX, $M	182	149	178
OPEX, $M/year	21	21	21
Revenues, $M/year	31	39	34
IRR, %	5	12	7
ROI, %	2	9	4
EBITDA, $M/year	11	18.5	14.3
EBITDA margin, %	36	47	42
Payback period, years	11.3	6.2	8.9

CFB = circulating fluidized bed; RC = rotating cone; MFB = mechanically assisted fluidized bed; CAPEX = capital expenditure; OPEX = operating expenses; IRR = internal rate of return; ROI = return on investment; EBIDTA = earnings before interest, taxes, depreciation, and amortization.

IX. Economic results for implementation scenario 1: fast pyrolysis standalone.

ysis is integrated into a new sawmill are presented in **Table X**. In the OPEX, the costs of operations related to the sawmill have been added. They include wood purchase, wood transport, and the operations necessary for the functioning of the sawmill. The costs of wood purchase for fast pyrolysis have been removed because, as explained in the case study presentation, the residues coming out of the sawmill will be used as input biomass for fast pyrolysis. These factors result in a higher OPEX, but the revenues are proportionally higher as well because the sale of lumber helps with the ROI.

A significant improvement can be observed in the IRR for each technology compared to scenario 1. Assuming that an IRR of 20% is necessary for a project to be profitable, all technologies can be profitable when integrated within an existing sawmill.

As for the other KPIs, significant improvements are observed as well, underlining the benefits of an integration. This implementation scenario is closer to profitability than the first one. The payback period is very much shorter than in the first case (3 years vs. 11 years for CFB).

In the third implementation scenario, policy incentives were considered in the selling price of bio-oil sold in the United States to obtain RIN credits. **Table XI** shows the results for the RIN credits that can be obtained for each technology. The CAPEX is $3M higher for each technology to accommodate bio-oil transport from Canada to the United States. It is important in this case to consider the energy

	Base Line Process FP-400: CFB	FP-400: RC	FP-400: MFB
Lumber, metric tons/day	365.5		
CAPEX, $M	182	149	178
OPEX, $M/year	62	63	62
Revenues, $M/year	107	112	110
IRR, %	23	29	24
ROI, %	21	30	23
EBITDA, $M/year	45.3	49.5	48.6
EBITDA margin, %	43	44	44
Payback period, years	3.2	2.5	2.9

CFB = circulating fluidized bed; RC = rotating cone; MFB = mechanically assisted fluidized bed; CAPEX = capital expenditure; OPEX = operating expenses; IRR = internal rate of return; ROI = return on investment; EBIDTA = earnings before interest, taxes, depreciation, and amortization.

X. Economic results for implementation scenario 2: fast pyrolysis integration with a sawmill.

	Base Line Process FP-400: CFB	FP-400: RC	FP-400: MFB
Lumber, metric tons/day	365.5		
CAPEX, $M	185	152	181
OPEX, $M/year	62	63	62
Product revenues, $M/year	108	127	110
RIN revenues, $M/year	43	44	56
IRR, %	38	51	43
ROI, %	44	70	53
EBITDA, $M/year	88.8	108.5	104.7
EBITDA margin, %	59	63	63
Payback period, years	1.7	1.2	1.4

CFB = circulating fluidized bed; RC = rotating cone; MFB = mechanically assisted fluidized bed; CAPEX = capital expenditure; OPEX = operating expenses; RIN = renewable identification number; IRR = internal rate of return; ROI = return on investment; EBIDTA = earnings before interest, taxes, depreciation, and amortization.

XI. Economic results for implementation scenario 3: fast pyrolysis integration with a sawmill + full valuation of bio-oil.

content of the bio-oil obtained with different technologies. As previously explained, the bio-oil extracted from the MFB technology is almost dry, and its energy content is higher, which explains the increased RIN revenues. As for the CFB and RC technologies, even if RC has more bio-oil extracted, because the moisture in the bio-oil is 22%, the energy content is lower, meaning that fewer RINs will be obtained. For CFB, the RIN revenues are $1M less than those of RC because of the smaller quantity of bio-oil. The larger IRR is associated with the RC technology because the CAPEX is the lowest, even if the MFB has the largest revenues. The EBITDA associated with the MFB configuration is $9M higher than the CFB one, which is mainly due to the larger revenue coming from the RIN credits. Compared to implementation scenario 2, remarkable performance improvements were achieved, largely due to the bio-oil incentives.

The fourth implementation scenario reflects the integration of a progressive condensation unit with the fast pyrolysis process, providing a dried, more stable, and more efficient oil. The order-of-magnitude capital cost of the progressive condensation train has been estimated at $10M for CFB and RC (it is already in the base case of MFB). It has been assumed that the bio-oil is dried to under 10% moisture. As presented in Table V, the selling price of bio-oil is based on the heavy fuel oil (HFO) price on the market as in the first case, and the price of bio-oil will be based on

	Base Line Process FP-400: CFB	FP-400: RC	FP-400: MFB
Upgraded bio-oil, metric tons/day	216 (10% moisture)	232 (10% moisture)	216 (almost dry)
CAPEX, $M	187	155	178
OPEX, $M/year	21	22	21
Revenues, $M/year	51	60	67
IRR, %	15	24	23
ROI, %	11	22	22
EBITDA, $M/year	29.5	37.9	46.3
EBITDA margin, %	58	63	69
Payback period, years	5	3.3	3.1

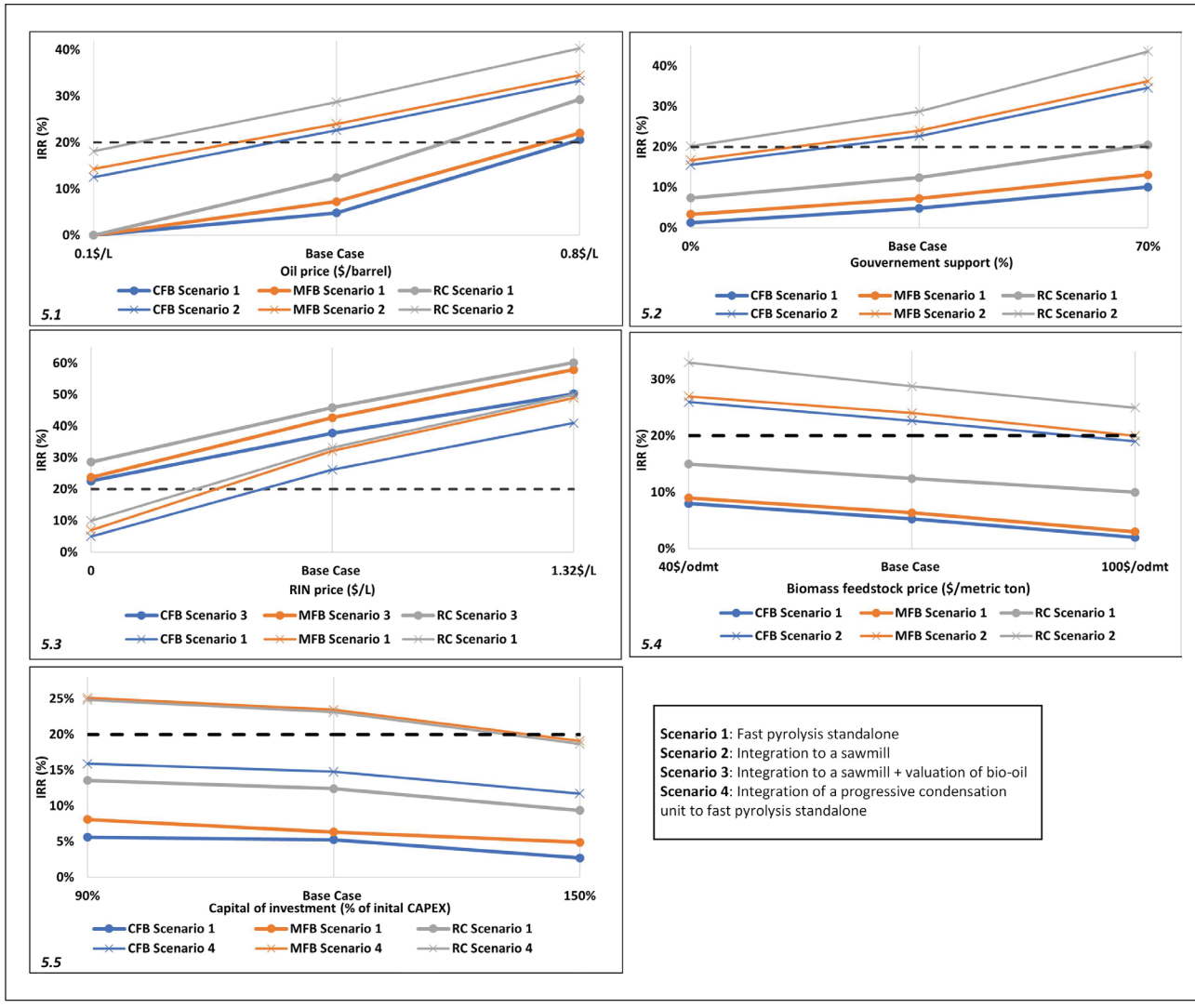
CFB = circulating fluidized bed; RC = rotating cone; MFB = mechanically assisted fluidized bed; CAPEX = capital expenditure; OPEX = operating expenses; IRR = internal rate of return; ROI = return on investment; EBIDTA = earnings before interest, taxes, depreciation, and amortization.

XII. Economic results for implementation case 4: fast pyrolysis + progressive condensation unit

Parameter		Value	Justification
Crude oil price	Minimum	0.10$/L	$16/barrel –Temporary crash in oil price
	Base case	0.40$/L	$70/barrel – Long-term estimate [34]
	Maximum	0.80$/L	$140/barrel – Oil price rise
Assumed government support towards capital costs	Minimum	0%	Hypothesis of no government support
	Base case	40%	Assumed support from all levels of government
	Maximum	70%	Maximum support by government
RIN pricing	Minimum	0	Base case considered D3 renewable identification number (RIN) value in the reference year (e.g., 2.5 CAN$/RIN gal in 2020), depending on available volumes of produced cellulosic biofuels, demand intensity, and other factors [35]
	Base case	$0.66/L	
	Maximum	$1.32/L	
Biomass feedstock price	Minimum	$40/ton	Low cost of biomass
	Base case	$70/ton	Base case
	Maximum	$100/ton	High biomass cost found for higher volumes, more complex logistics
Estimate of capital investment	Minimum	90%	Slight underestimation of capital costs
	Base case	100%	As estimated for each case and technology
	Maximum	150%	Assumption of additional costs due to potential integration of new equipment or an update

XIII. Parameters studied for the sensitivity analysis.

the lower heating value (LHV) ratio between HFO and pyrolysis oil. As the quality of the oil is improved by the progressive condensation unit (10% vs. 22% moisture), the selling price will be higher for the CFB and RC configuration. The selling price will be higher for the oil from MFB because the bio-oil is almost dry at the end, unlike the other two technologies. The results are presented in **Table XII**. As a conclusion, the revenues show great improvement compared to implementation scenario 1, where the higher IRR was 12%. In this case, RC and MFB processes are near profitability threshold, because the IRR is higher than 20% in both cases. By looking at the CFB and RC reactors, it is possible to determine that the CAPEX increased by 3%–4% vs. an increase of 32%–35% in revenues. The addition of the progressive condensation unit greatly improved revenues. A significant improvement can also be observed for the EBITDA and the payback period, where the longest period is related to the CFB process (5 years). In the first



5. Sensitivity analysis results: (5.1) on the oil price; (5.2) for government support towards the capital cost; (5.3) for renewable identification number (RIN) price incentives on bio-oil; (5.4) on the biomass feedstock price; and (5.5) for the actual capital cost vs. estimate of capital investment.

implementation scenario, the payback period of the same technology was 11 years.

With the presentation of these cases and their results, it was possible to analyze income diversification and how it can drive project profitability. Furthermore, it was possible to understand the importance of selling not only locally, but also outside the territory to expand the market shares. Finally, the integration of downstream processing systems, such as the progressive condensation system, led to noteworthy performance improvements of fast pyrolysis processes.

Sensitivity analysis

A sensitivity analysis was completed considering key parameters related to the economic viability of the technologies under the various implementation scenarios in order to help identify risks and their mitigation. **Table XIII** summarizes these parameters and the values considered for the sensitivity analysis, where the impact on IRR was estimated. **Figures 5.1–5.5** show the results for the different scenarios, noting that the scale for IRR changes between the different figures. For each parameter, two scenarios of the four presented previously were chosen to be analyzed, depending on the implication of the parameter on the implementation scenario.

There are three parameters that substantially improve the IRR when they are at their higher values for the sensitivity analysis: bio crude oil price, government support for capital cost, and the incentives on the bio-oil represented by the RINs value.

For implementation scenario 1, where fast pyrolysis standalone is considered, a higher oil selling price brings the CFB and MFB technology near economic viability (assumed to be 20% IRR). On the other hand, a lower selling

Implementation Scenario	CFB	RC	MFB
1. Fast pyrolysis stand-alone CAPEX ($M)/IRR (%)	182/5	149/12	178/7
2. Fast pyrolysis integrated with a sawmill CAPEX ($M)/IRR (%)	182/23	149/29	178/24
3. Fast pyrolysis integrated with a sawmill + full valuation of bio-oil CAPEX ($M)/IRR (%)	185/38	152/51	181/43
4. Fast pyrolysis + progressive condensation unit CAPEX ($M)/IRR (%)	187/15	155/24	178/23

CFB = circulating fluidized bed; RC = rotating cone; MFB = mechanically assisted fluidized bed; CAPEX = capital expenditure; IRR = internal rate of return.

XIV. Summarization of the implementation scenarios studied and their most valuable results.

price brought all the technologies under the 20% target IRR, but none of the scenarios had a large negative cash flow, so the process would be robust for short-term (very) low selling prices. The profitability of the fast pyrolysis process is sensitive to the crude oil price. Implementation scenario 4, where the progressive condensation unit was integrated, shows a similar trend. Doubling the price of HFO can bring the IRR to a very attractive 44% for RC, 40% for MFB, and 33% for CFB, further emphasizing the advantage of having higher bio-oil quality at the end of the process.

Government support for capital cost is critical. In the first scenario, the RC technology was economically attractive if government support reached 70%. For the second implementation scenario, the absence of government aid has noticeable consequences on process profitability for all three technologies. On the other hand, maximum support creates an evident improvement in the three configurations IRRs.

The impact of bio-oil price incentives examined for implementation scenario 3 has shown that having higher-value RIN credits definitely brings the profitability to a very high IRR, which even for the CFB technology is a great opportunity. However, it is crucial to understand how the variability of these parameters can either bring a process close to non-profitability or create high revenue and good economic viability. Besides studying this parameter for case 3, these credits were also added to implementation scenario 1, which was the fast pyrolysis standalone case, to see how selling the biol-oil to the United States to obtain the RIN credits could affect profitability. Adding the RINs to the first scenario effectively brings all three technologies to profitability. This shows that the fast pyrolysis process standalone case can be profitable, but only if incentives for bio-oil are there and can be used.

The last two parameters studied for the sensitivity analysis were the biomass price and government support for capital cost. Figure 5.4 shows that expensive biomass feedstock further reduces the IRR, as would be expected. The impact of increased capital investment costs also reduces the ROI as expected, but not to the degree found for other more capital-intensive biofuel processes. History has shown that the actual capital cost for projects can be substantially higher than early-stage estimates, and it is important to consider this possibility. A 50% higher cost was considered.

Finally, one salient factor related to these results concerns policy linked to biofuels, including incentives for low-carbon fuel projects. Following recent COP26 discussions, countries and companies are increasingly making commitments to reach net zero GHG emissions by 2050. Biofuels can contribute to achieving these net-zero targets. In the United States, while there has been investment in low-carbon fuels, more investment is still needed [42]. The Inflation Reduction Act, signed in United States in August 2022, will help private companies produce more renewable energy by using incentives to combat climate change, with a total investment of $370 billion [43].

CONCLUSIONS

In recent years, most fast pyrolysis technologies have started to be implemented at pre-commercial scale, but the economic viability is still a challenge due to various risks, uncertainties, and the need for a supportive regulatory environment. This study examined three fast pyrolysis technologies having different value-added products in order to determine the general conditions for economic viability. With the traditional CFB fast pyrolysis technology considered, biochar and bio-oil are produced. The RC technology produces steam for cogeneration in addition to bio-oil. Finally, the MFB technology produces biochar, pyrolysis water (which in this case has not been fully valued, but might be in the future), and lastly bio-oil, which is almost dry in the process configuration considered.

Four implementation scenarios were considered with phased implementation to examine integration with a sawmill, incentives for bio-oil, and integration of a progressive condensation unit. The LBA methodology was used to es-

timate the costs, better ensuring that relative costs were estimated for comparisons. **Table XIV** summarizes the results for the assumptions considered.

For implementation scenario 1, where the standalone fast pyrolysis technology platform was considered, all three technologies had a marginal return under a base case scenario of 40% support for capital cost and a premium on biocrude selling price typical of what one might expect from RINs. This captures an important reason as to why fast pyrolysis has not yet been more widely implemented, even considering the potential GHG emission reduction benefits that could be realized.

The second implementation scenario took into account the integration of the fast pyrolysis plant to an existing sawmill. An improvement was observed for the IRR for all three technologies, where their values were higher than 20%. Implementation scenario 3 was similar to scenario 2 in that it integrated fast pyrolysis to a sawmill. However, scenario 3's addition of RINs credits to its portfolio from sale of bio-oil in the Unites States and a full valuation of the product made it an especially attractive investment.

However, in the last two scenarios, when bio-oil quality was considered, MFB showed an improvement in profitability (43% for the third scenario vs. 24% for the second one). The implementation scenarios demonstrated that implementing fast pyrolysis processes in a sawmill or adding incentives to bio-oil evidently improves the outcome. Specifically, the progressive condensation unit improves economic viability for all fast pyrolysis process configurations, because the quality of the bio-oil substantially increases the revenues while increasing the CAPEX by only a small amount.

Finally, with the sensitivity analysis, the importance of having government support and incentives for the bio-oil price was shown. These policies are essential for a project's economic viability. The price of barrel can also impact the IRR, as a lower price means a lower selling price for the bio-oil produced, thereby demonstrating the importance of an updated and robust regulatory environment.

In conclusion, fast pyrolysis processes undoubtedly represent an opportunity for the future of bio-oil and for achieving net-zero goals. **TJ**

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ABOUT THE AUTHORS

We studied this topic because we wanted to explore techniques for assessing biorefinery technology platforms at different technology readiness levels. There is little applied research in the area of biorefinery technology comparisons for many reasons, including that high levels of uncertainty in technology information and capital/operating costs are difficult to interpret. We used a methodology that requires a strong understanding of the implicated technology, engineering design, and Good Engineering Judgement to arrive at a practical methodology and result.

Through this study, we saw the importance of close and multidisciplinary team collaboration between the co-authors needed to arrive at good results. Our most interesting finding was that with careful application of the large block analysis (LBA) methodology, you can have good confidence in techno-economic results, even at the early design stage.

The methodology used here takes time to learn, but it can be executed by mill-level engineers. While data from the technology developers is needed, no sophisticated design and engineering systems are required.



Bele



Benali



Stuart

Our next step is to use the I-BIOREF software, used here in connection with techno-economics, at the criteria level for design decision-making between biorefinery technologies.

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APPENDIX A

Investment Costs	RC	CFB	MFB	Justification
	Million $			
Direct costs				
Equipment cost				
Feedstock handling and preparation	9.9			Same pre-treatment cost for every technology
Thermal fast pyrolysis system				
Reactor and auxiliaries	48	52	40	CFB has two fluidized beds. MFB has only one fluidized bed, which dissociates the temperature and the mixing.
Vapor phase train	13	9	18	More expensive for MFB because of the progressive condensation unit.
Biochar recovery system	-	10	10	Only CFB and MFB have biochar as a value-added product.
Total purchased equipment	71	81	78	
Construction	Included in equipment cost			
Service facilities	14.2	16	16	20% of total purchased equipment cost
Piping	-	6	6	8% of total purchased equipment cost
Electrical, control & instrumentation	4	4	4	5% of total purchased equipment cost
Total Direct Costs	**89**	**107**	**104**	
Indirect costs				
Engineering	13	16	16	15% of total direct costs
Construction management	11	13	12	12% of total direct costs
Owner's costs	3	3	3	3% of total direct costs
Startup & commissioning	2	2	2	2% of total direct costs
Total Indirect Costs	**28**	**34**	**33**	
Fixed capital investment	117	142	137	
Contingency	18	21	20	15% of fixed capital investment
Working capital	14	19	19	10% of total capital investment
Total Capital Investment	**149**	**176**	**208**	

RC = rotating cone; CFB = circulating fluidized bed; MFB = mechanically assisted fluidized bed.

A1. Detailed capital investment costs for economic analysis for a standalone fast pyrolysis plant.

APPENDIX A

Operating Costs	RC	CFB	MFB	Justification
	Million $			
Feedstock (biomass)	9.24			Same quantity of feedstock
Utilities				
Electricity	0.09	0.64	0.27	Higher demand in electricity for the CFB process due to the waste treatment unit
Steam	-	-	0.11	MFB: Steam used to heat the reactor
Water	0 .19	0.03	0.8	MFB: More water used to cool the reactor
Sand	0.20	0.91		
Operations				
Labor	1.28			12 operators and 1 supervisor
Laboratory charges	0.19			15% of labor
Maintenance				
Maintenance and repairs	4.47	3.10	3.69	3% of total capital investment
Operating supplies	0.67	0.46	0.55	15% of maintenance and repairs
Other expenses				
Plant operating overhead	1.73	1.31	1.49	30% of labor, maintenance, and repairs
Sales and marketing	0.42	0.32	0.36	5% of operations, maintenance, and plant operating overhead
Administrative fees	0.26			20% of labor
Insurance	0.60	0.70	0.83	0.4% of total capital investment
Taxes	1.49	1.76	2.08	1% of total capital investment
Total Operating Cost	**20.82**	**20.21**	**21.16**	

RC = rotating cone; CFB = circulating fluidized bed; MFB = mechanically-assisted fluidized bed.

A2. Detailed operating costs for economic analysis.

APPENDIX B

KPI	Definition	Interpretation	Equation
Profitability			
IRR	The internal rate of return (IRR) is the discount rate that makes the net present value of all cash flows from the biorefinery implementation equal to zero.	The higher the IRR, the more profitable the biorefinery is. As of the 2019 reference year, a typical threshold for the IRR of biorefinery projects is 20%.	IRR for which: $\sum_{i=0}^{Project\ lifetime} \frac{Cash\ Flow_{Year\ i}}{(1+IRR)^i} = 0$
ROI	Return on investment (ROI) is the ratio of the net value generated by a biorefinery plant over a given period, to the corresponding capital investment.	Negative values of ROI indicate that the project has not reached profitability but might be profitable in the future. The higher the ROI, the more profitable a biorefinery project is.	$ROI_{Year\ T} = \frac{Cumulative\ cash\ flow_{Year\ T}}{Cumulative\ capital\ investment_{Year\ T}}$
Robustness			
EBITDA	Earnings before interest, taxes, depreciation, and amortization (EBITDA) is the operating income that a biorefinery project generates, not accounting for depreciation and amortization expenses.	The EBITDA is a measure of the biorefinery project's financial performance, expressed as a cash profit (or deficit) from its operations. The higher the EBITDA, the higher is the potential of a biorefinery project to generate net profit.	EBITDA = Revenue-Operating Cost
EBITDA Margin	Ratio that shows the fraction of revenues that is available to cover non-operating expenses before accounting for depreciation and amortization.	Indicator of how financially robust a biorefinery project is, expressed based on cash generation from its operations. Higher values of EBITDA margin are preferred.	$\text{EBITDA margin} = \frac{EBITDA}{Revenue}$
Capital Efficiency			
CAPEX	The capital expenditure (CAPEX) is the total amount of capital invested to implement the biorefinery plant.	Measure of the capital intensity of a biorefinery process, considering government subsidies. Lower CAPEX generally implies a lower financing risk, because annual investments by private companies are usually budget-capped and access to external sources of funding is limited.	CAPEX = Fixed Capital Investment + Total Other Cost
Payback period	The payback period is the time required to recover the capital invested for implementing a biorefinery plant. It is calculated using the capital investment costs, annual revenue, and operating costs of the biorefinery plant at full capacity for the annual uptime provided.	The payback period is a measure of the project's ability to rapidly balance capital investment through cash flow generation. Shorter payback periods are preferred.	Year T for which: $\sum_{i=start-up\ year}^{T} Cash\ Flow_{Year\ i} = Total\ capital\ investment$

B1. Key performance indicators (KPIs) used for the techno-economic analysis.