Title

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Authors

Poddar, Tuhin K
Scown, Corinne D

Publication Date

2025-04-01

DOI

10.1016/j.copbio.2025.103258

Available online at www.sciencedirect.com

ScienceDirect

Current Opinion in
Biotechnology

Review

Technoeconomic analysis for near-term scale-up of bioprocesses

Tuhin K Poddar[1,2] and Corinne D Scown[1,2,3,4]

Growing the bioeconomy requires products and pathways that are cost-competitive. Technoeconomic analyses (TEAs) aim to predict the long-term economic viability and often use what are known as n^{th} plant cost and performance parameters. However, as TEA is more widely adopted to inform everything from early-stage research to company and investor decision-making, the n^{th} plant approach is inadequate and risks being misused to inform the early stages of scale-up. Some methods exist for conducting first-of-a-kind/pioneer plant cost analyses, but these receive less attention and have not been critically evaluated. This article explores TEA methods for early-stage scale-up, critically evaluates their applicability to biofuels and bioproducts, and recommends strategies for producing TEA results better suited to guiding prioritization and successful scale-up of bioprocesses.

Addresses
[1] Life-cycle, Economics, and Agronomy Division, Joint BioEnergy Institute, Emeryville, CA 94608, United States
[2] Energy & Biosciences Institute, University of California, Berkeley, CA 94720, United States
[3] Biological Systems and Engineering Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, United States
[4] Energy Analysis and Environmental Impacts Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, United States

Corresponding author: Scown, Corinne D (cdscown@lbl.gov)

Current Opinion in Biotechnology 2025, **92**:103258

This review comes from a themed issue on **Energy Biotechnology**

Edited by **Gregg Beckham** and **Alissa Bleem**

Available online xxxx

https://doi.org/10.1016/j.copbio.2025.103258

Introduction

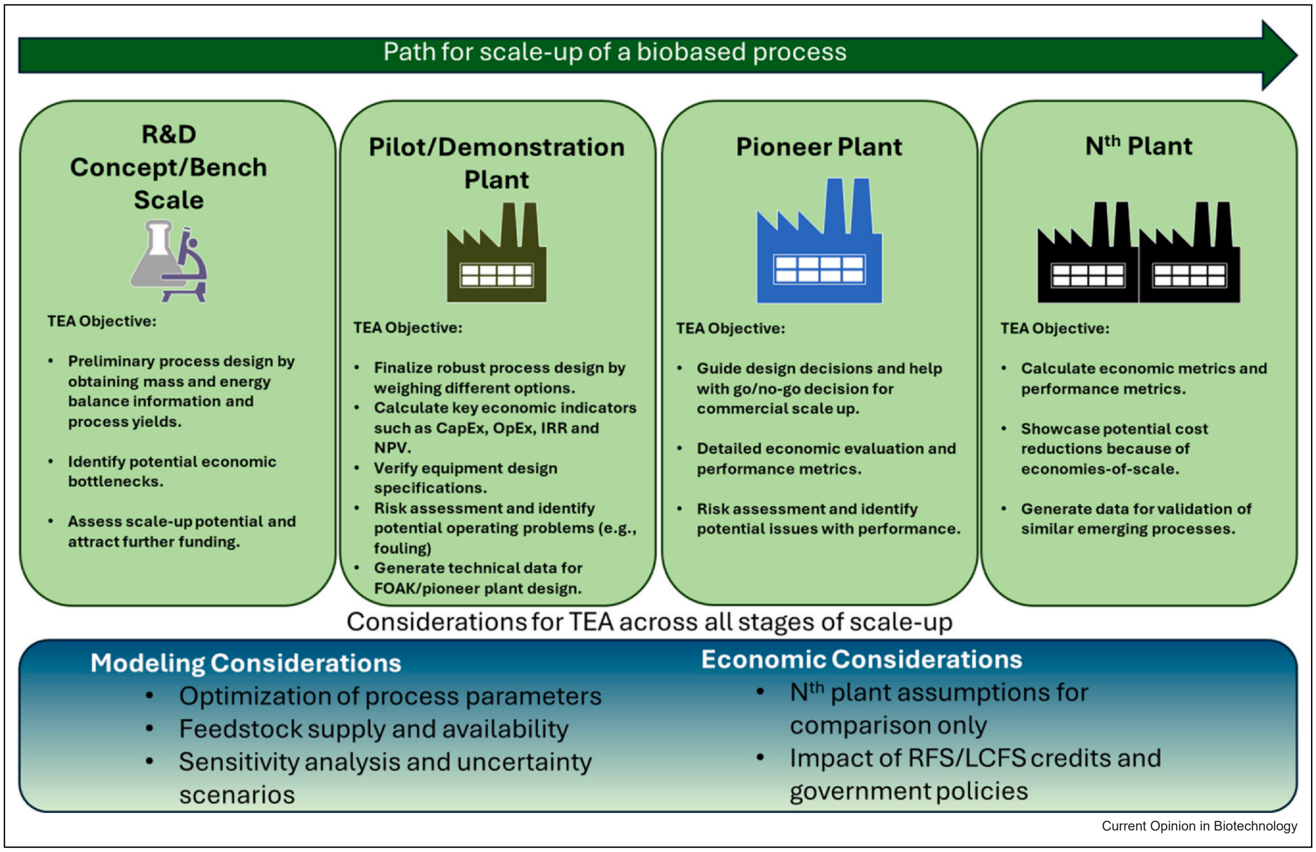
The development of low-carbon bioenergy and bioproducts is vital to reducing global greenhouse gas emissions from sectors, including transportation and chemical manufacturing [1]. Deep decarbonization requires a transition that extends beyond first-generation production and leverages new research and development (R&D) to convert sustainably harvested biomass and waste resources to fuels and products [2,3]. The typical trajectory of a bioprocess facility's scale-up begins with process innovation and development at the lab scale, followed by a pilot plant, a demonstration facility, a first-of-a-kind (FOAK, also referred to as a pioneer) plant, and, finally, what is known as an n^{th} plant, which is typically the fifth commercial plant and onward that is built and brought online [4]. By the time a bioprocess facility is deemed an n^{th} plant, economies of scale, reliable plant performance, along with stable feedstock availability and product output, all bring costs down relative to the FOAK plant [5].

Technoeconomic analysis (TEA) is an approach used to gain early insights into the long-term economic viability of biobased production pathways using a combination of engineering design, computer simulations, and performance data generated in the R&D phase [6]. TEAs, particularly those done by researchers, often exclusively use n^{th} plant assumptions for several reasons: (1) researchers are motivated to prove the viability of their own technologies and (2) FOAK plants are understood to be costly, carry the risk of delays, and have unexpected cost overruns that are difficult to predict. However, the exclusive focus on n^{th} plant analysis misses a critical opportunity to inform and prioritize R&D based on the metrics of greatest importance at the early stages of scale-up, where other factors may play an outsized role in the costs. Process simplicity, reduced capital expenditures (CapEx), and minimizing reliance on technologically immature unit processes are all likely to be important. Conducting FOAK and n^{th} plant TEAs in parallel can address this gap, and there are several examples of this in the literature [7–12]. In this paper, we review recent efforts to assess the economic performance of bioprocesses at various stages of scale-up, evaluate these methods, and highlight shortcomings that can be addressed in the future.

Path to commercialization and scale-up of bioenergy and bioproduct facilities

The construction and operation of a FOAK (pioneer) plant is the primary hurdle that stands in the way of successful commercialization of a new bioprocess. The typical stages of scale-up of a biobased process are shown in Figure 1. The FOAK plant plays an important role in proving that a process can work at scale and demonstrating the robustness of the feedstock supply chain as well as the off-take value chain [4,13]. FOAK plants,

Figure 1



Progression of scale-up for bioprocess processes and other considerations for TEAs.

particularly for bioprocesses, may not achieve competitive product selling prices, but they are critical as a bridge from the R&D stage to the commercial stage.

Reliance of technoeconomic analyses on n^{th} plant assumptions

Across all stages of bioprocess R&D and scale-up, TEA is frequently used to gauge the likelihood of success and identify technical and cost bottlenecks [14]. Much of the TEA community, particularly those working on biofuels and bioproducts, has coalesced around a set of standard input parameters for n^{th} plant analyses. These analyses include (but are not limited to) articles by Kim *et al.*, Dutta *et al.*, Jones *et al.*, and Tan *et al.* [15–18]. N^{th} plant assumptions based on more established technologies have also been adapted for emerging areas of bioprocess R&D, including algal biofuels and integrated biorefineries [19,20]. When researchers apply n^{th} plant assumptions, costs that would be incurred for FOAK plants are not included, such as special financing, large contingency costs, and longer start-up times. The n^{th} plant functions as a common basis for comparison and represents a well-defined hypothetical plant with the calculated costs being indicative of a future scenario when the technologies involved are mature, and several similar plants have already been built and are operating [21]. Table 1 is a summary of the main n^{th} plant assumptions that have been used in TEA studies in recent years and values that would likely need to be adjusted for an FOAK analysis.

The economic assumptions and operating conditions assumed for an n^{th} plant do not all apply to FOAK plants, as noted in Table 1. For example, a 90% on-stream percentage is virtually impossible for an FOAK plant after start-up, and these facilities can take up to 18–24 months to reach a stable production capacity. Economically, an n^{th} plant has lower financing costs and low contingency costs relative to an FOAK plant, which carries more uncertainty and risk [22].

Some studies have compared bioprocess TEAs using both the n^{th} plant and a FOAK scenario [9,10,22], but the n^{th} plant remains the default for most publications. Humbird *et al.* [23] argued that including higher costs associated with FOAK plants, like risk financing, longer start-up times, etc., all of which are outside the control of scientists and engineers seeking to optimize the process,

Table 1

The typical n^{th} plant assumptions for bioprocess TEA [8] and applicability to FOAK plants [20].

Description	Assumed value for n^{th} plant	Potential adjustments for FOAK
Internal rate of return (IRR)	10%	Higher IRR between 10% and 20%
Plant financing by equity/debt	40%/60% of total capital investment	Higher equity/debt ratio
Plant life	30 years	Between 20 and 30 years
Income tax rate	21% (35% before January 2018)	No change
Interest rate for debt financing	8.0% annually	Higher interest rate
Term for debt financing	10 years	10–15 years
Working capital cost	5.0% of fixed capital investment (excluding land purchase cost)	Higher percentage of fixed capital investment
Depreciation schedule	7-year Modified Accelerated Cost Recovery System (MACRS) schedule	No change
Construction period (spending schedule)	3 years (8% Y1, 60% Y2, 32% Y3)	Longer construction period
Plant salvage value	No value	No change
Start-up time	6 months	18–24 months
Revenue and costs during start-up	Revenue = 50% of normal Variable costs = 75% of normal Fixed costs = 100% of normal	Lower revenue and higher variable and fixed costs
On-stream percentage after start-up	90% (7884 operating hours per year)	Lower on-stream percentage

obscures the impacts of process improvements on overall economics. While this critique of FOAK TEA is valid, it discounts the role that R&D can play in producing processes that increase the likelihood of success during the FOAK stage, provided researchers have robust TEA results to guide their efforts.

Existing methods used for technoeconomic analysis of first-of-a-kind facilities

The RAND method developed by Merrow *et al.* [24] in 1981, remains the most commonly used method for estimating FOAK costs [6,8], is based on the statistical regression analysis of data from 44 process plants to derive empirical equations to help estimate the higher costs and performance shortfall of FOAK plants. The RAND method relies on more detailed TEA outputs for an n^{th} plant design and provides adjustment factors to estimate costs and performance for the FOAK plant (referred to in the method as pioneer plant). A key drawback of this approach is the length of time that has passed since it was updated. Although it is possible to adjust for inflation, some costs relevant to industrial facilities may have changed more/less than inflation. The two main predictive equations used by the RAND method are shown in Equation 1 [25]. Table 2 provides variable definitions and quantitative ranges:

$$\textit{Cost growth factor} = 1.12196 - 0.00297 * PCTNEW - 0.02125 * IMPURITIES - 0.01137 * COMPLEXITY + 0.00111 * INCLUSIVENESS + C * PROJECT\ DEFINITION \quad (1)$$

$$\textit{Plant performance factor} = 85.77 - 9.69 * NEWSTEPS + 0.33 * BALEQS - 4.12 * WASTE - 17.91 * SOLIDS \quad (2)$$

Equation 1 is used to inflate the total capital investment (TCI) for a FOAK plant compared to the estimated n^{th} plant cost, which analysts must still estimate before using the RAND method. By inputting values for the variables in Equation 1, a cost growth factor is calculated, which then can be used to estimate the TCI of the FOAK plant as shown below in Equation 3:

$$TCI_{Pioneer} = TCI_{nthplant} / \textit{cost growth factor} \quad (3)$$

At the extreme end of each input enumerated in Table 2 (most complexity, new processes, challenges with impurities, etc.), the TCI for a FOAK plant as calculated with Equation 3 will be 5.1 times the TCI of the n^{th} plant. To estimate the shortfall in plant performance, Equation 2 is used to calculate a performance factor, which is used in Equation 4 to get the production capacity of a FOAK plant:

$$\textit{Plant capacity pioneer} = \textit{Nameplate capacity} * \textit{plant performance factor} \quad (4)$$

Recent studies applying the RAND method have mostly used it to estimate the FOAK TCI, reported alongside results for the n^{th} plant. Snowden-Swan *et al.* [8] assessed hydrothermal processing of wastewater sludge pathway and found that the TCI for the pioneer plant would cost 75% more than the n^{th} plant version and the on-stream factor of the pioneer plant would be approximately 9% less than the n^{th} plant. A similar methodology was used in recent studies by Cervi *et al.* [26], Mukherjee *et al.* [27], Huang *et al.* [28], and Tao *et al.* [9] and in older studies by Kazi *et al.* [10,22], Swanson *et al.* [21], Wright *et al.* [29], and Anex *et al.* [11] to estimate the FOAK/pioneer plant costs.

Table 2 lists the inputs for each of the variables in Equations 1 and 2. Some of the key variables like

Table 2

Variables used in the RAND method to estimate pioneer plant costs and their possible values [25].

Cost growth variables	PCTNEW (%)	Percentage of total capital cost for equipment that has not been commercially proven/demonstrated as determined in the more detailed nth plant analysis.	0–100 (entered as a whole number corresponding to the percentage)
	IMPURITIES (subjective rating)	Issues that may arise from the buildup of impurities as well as corrosion and abrasion effects.	0–5
	COMPLEXITY (subjective rating)	Number of steps in the process that are continuously linked.	1–11 according to the data from reference plants used in developing the RAND model.
	INCLUSIVENESS (%)	Percentage of prestartup inventory, personnel, and land purchased cost. The lower the inclusiveness, the more capital intensive the process.	0–100 (entered as a whole number corresponding to the percentage)
	C (select 1 of the 2 values)		−0.04011 for commercial/ precommercial; −0.06361 for processes with substantial R&D component
	PROJECT DEFINITION (subjective rating)	Basic plant layout, process flow conditions, major equipment definitions, site-specific information, and evaluations. The lower the rating, the more well defined the process.	2–8
Plant performance variables	NEWSTEPS (number of unit processes)	Number of process step blocks in the plant that are new in commercial use.	0+
	BALEQS (%)	Percentage of heat and mass balance equations in the n^{th} plant analysis that are based on actual data from previous commercial plants.	0–100
	WASTE (subjective rating)	Difficulty of design that might be encountered with waste handling.	0 (none) to 5 (severe)
	SOLIDS (binary)	A value of 1 if the plant is expected to handle solids either as a feedstock, intermediate material, or as a product. Value of 0 otherwise.	1 or 0

IMPURITIES (which represent the difficulty of handling impurities in the process), PROJECT DEFINITION, and WASTE handling are subjective in nature. To address this subjectivity, Tao *et al.* and Wright *et al.* analyzed the costs of their FOAK facility under three different scenarios using different values. Both studies have used 'most probable', 'pessimistic', and 'optimistic' scenarios for handling impurities and for project definition. One component that is important for bioprocesses that rely on solid biomass feedstocks and/or other organic waste streams is heterogeneity and unpredictability of the incoming waste streams, and this is arguably missing from the variables in Table 2.

Merrow *et al.* noted that the RAND method is based on data collected from 44 oil, chemical, and mineral processing plants, which are not necessarily representative of bioconversion facilities [30]. There is little empirical evidence in the literature to suggest that the predictive equations for cost growth and plant performance are accurate and, while one article by Morrison *et al.* described the RAND method as accurate in predicting pioneer biofuel plant costs and performance [31], they provided no quantitative evidence to support this claim. Snowden-Swan *et al.* [8] were careful to mention following their pioneer plant analysis, that the use of the RAND method was only for obtaining an initial estimate of a pioneer facility.

Another method that has been used in recent TEAs for FOAK plants, which captures the impact of economies of scale, but no other factors, is the use of the power law scaling relationship, an established mathematical method, which extrapolates equipment size from one scale to another based on historical data. It is described by Equation 5 below [32]:

$$C_2 = C_1 * \left(\frac{S_2}{S_1}\right)^n \tag{5}$$

where C = cost, S = equipment size/capacity, and n = scaling exponent.

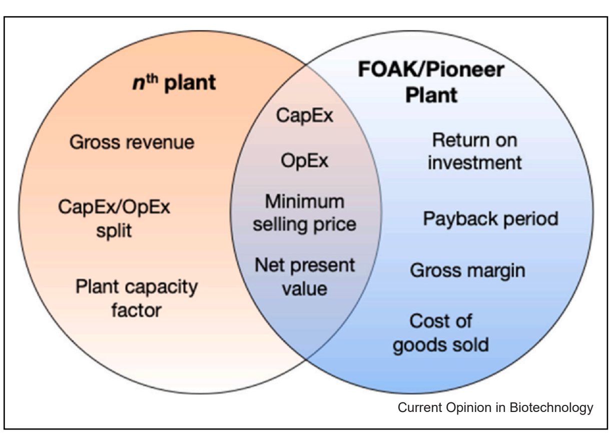
Kreutz *et al.* [33] used the power law scaling equation to estimate FOAK costs by calculating the bare erected costs of individual plant components of a lignite/biomass-to-jet fuel process plant using data obtained from a demonstration plant. Such an approach assumes the FOAK plant closely resembles a demonstration plant, but larger and is far too simplistic to incorporate real-world technology scaling behavior [34]. The power law scaling method is most effective when plants that closely resemble the new technology already exist and therefore can provide the necessary historical data required for the relationship to provide useful predictive costs. The bioeconomy is still far too young for this method to be applied effectively, given the limited data available [34].

Opportunities for improving first-of-a-kind analyses

Although this review has offered some critiques of the RAND method, its simplicity makes it easy to adopt as an add-on for any study doing a more conventional n^{th} plant TEA. At the most basic level, the RAND method could be improved by conducting an updated regression with data from more recent projects and, ideally, a version could be better tailored to bioprocesses specifically. Updating the regression, while mathematically simple, requires confidential data that are likely difficult to obtain [35].

To expand and improve the TEA community's approach for FOAK analyses, an updated regression is necessary but not sufficient. Researchers need to explore FOAK-relevant metrics. Scown *et al.* [14] noted a gap between economic metrics used within the research community and those valued by industry. Even within the research and industry communities, there is no firm consensus on the most relevant metrics or even how these metrics are calculated. For example, Konzock and Nielsen [36] discussed the impact of process titers, rates, and yields on the cost of goods sold (COGS), which they state includes depreciation of R&D costs. However, most sources indicate that R&D is not included in COGS, which is a useful FOAK-level parameter to help assess market competitiveness [37]. There are core TEA metrics, including capital expenditures (CapEx), operating expenditures, net present value, and minimum selling price of the product, that are relevant for the FOAK through n^{th} plant. Other metrics are more relevant for a FOAK plant, while others are applicable to describe an n^{th} plant, as shown in Figure 2. For example, profitability indicators, such as return on investment, gross margin, and payback period, are particularly important for securing investments necessary to build FOAK plants. A recent work by Hoey *et al.* highlighted the use of payback period and its sensitivity to production scale to evaluate the financial viability of different ethanol production processes [38].

Figure 2



Key economic metrics relevant for TEA studies for n^{th} and FOAK plants.

In addition to updating the RAND method and exploring a broader set of economic metrics, another important advancement in FOAK TEA methodology could be the development of design cases that better represent FOAK plants [39]. These design cases require better agreement as to what scale an FOAK model should represent; there is no agreement on whether an FOAK facility should be modeled at the same scale as an n^{th} plant or considerably smaller (e.g. one-tenth the size). The scale impacts design choices, as highlighted by Humbird *et al.* for biomass pyrolysis [40]. Additionally, FOAK plants may also rely on more off-the-shelf technologies or opt to use outside entities to handle their wastewater or solid waste to further reduce risk and CapEx.

Whether TEA is being used by early-stage researchers to gauge the viability of a new technology or applied by companies seeking to commercialize a new bioprocess, there are clear benefits to expanding the scope of analysis beyond n^{th} plant assumptions. FOAK analyses can uncover avenues of research that may be critical to reducing risk and complexity in early scale-up that would otherwise have gone unexplored. The results also provide a clearer picture of a technology's potential, which will lead to better-informed investments and policy decisions.

CRediT authorship contribution statement

Tuhin Poddar: Visualization, Writing – Original draft preparation. **Corinne Scown:** Conceptualization, Supervision, Funding acquisition, Writing – review & editing.

Data Availability

No data were used for the research described in the article.

Declaration of Competing Interest

C.D.S. has an interest in Cyklos Materials.

Acknowledgements

This work was part of the Department of Energy, Joint BioEnergy Institute (https://www.jbei.org) supported by the U.S. Department of Energy, Office of Science, Office of Biological and Environmental Research, through Contract DE-AC02–05CH11231 between Lawrence Berkeley National Laboratory and the U.S. Department of Energy. This work was also supported by the Department of Energy Bioenergy Technologies Office. The United States Government retains and the publisher, by accepting the article for publication, acknowledges that the United States Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this manuscript or allow others to do so, for United States Government purposes. This research received support through Schmidt Sciences, LLC, with support from the Foundation for Food & Agriculture Research.

References and recommended reading

Papers of particular interest, published within the period of review, have been highlighted as:

- • of special interest
- •• of outstanding interest

1. SAF Rules of Thumb; [2023].

2. Corrêa CEF, Santos DDCLP, Bomtempo JV, Alves FC: **The challenges of using lignocellulosic biomass in pioneer industrial plants**. *Biofuels Bioprod Bioref* 2024, **18**:9-17.

3. Bioenergy Technologies Office Multi-Year Program Plan, March 2016. 2016.

4. 2023 Multi-Year Program Plan; Energy gov. 2023.
•
A Department of Energy report that outlines the strategies the Bioenergy Technologies Office plans to undertake to meet the goals set for decarbonization by replacing fossil fuels with low-carbon biofuel alternatives. The report describes the various stages of scale-up needed for bioenergy facilities today and highlights the importance of modeling and TEA as tools for guiding scale-up.

5. Balan V: **Current challenges in commercially producing biofuels from lignocellulosic biomass**. *ISRN Biotechnol* 2014, **2014**:1-31.

6. Phillips SD, Jones SB, Meyer PA, Snowden-Swan LJ: **Techno-economic analysis of cellulosic ethanol conversion to fuel and chemicals**. *Biofuels Bioprod Bioref* 2022, **16**:640-652.

7. Singh N, Singhania RR, Nigam PS, Dong C-D, Patel AK, Puri M: **Global status of lignocellulosic biorefinery: challenges and perspectives**. *Bioresour Technol* 2022, **344**:126415.

8. Snowden-Swan L, Schmidt A, Fuller C, Anderson D : Hydrothermal
•• Processing of Wastewater Solids (HYPOWERs) Project Preliminary Techno- Economic Analysis; 2024.
A recent TEA study that has used the RAND method to calculate the pioneer plant costs for a conversion pathway to convert wastewater solids to produce biocrude oil and upgrading to transportation fuel blendstocks. This study shows that the RAND method is still used as recently as 2024 as a tool for comparison between pioneer and n^{th} plants.

9. Tao L, Markham JN, Haq Z, Biddy MJ: **Techno-economic analysis for upgrading the biomass-derived ethanol-to-jet blendstocks**. *Green Chem* 2017, **19**:1082-1101.

10. FK Kazi, J Fortman, R Anex, G Kothandaraman, D Hsu, A Aden, A Dutta. **Techno-Economic Analysis of Biochemical Scenarios for Production of Cellulosic Ethanol.** 2010. Doi:10.2172/982937.

11. Anex RP, Aden A, Kazi FK, Fortman J, Swanson RM, Wright MM, Satrio JA, Brown RC, Daugaard DE, Platon A, *et al*.: **Techno-economic comparison of biomass-to-transportation fuels via pyrolysis, gasification, and biochemical pathways**. *Fuel* 2010, **89**:S29-S35.

12. Howe C, Rolfes E, O'Dell K, McMurtry B, Razdan S, Otwell A: **Pathways to Commercial Liftoff: Sustainable Aviation Fuel**. U.S. Department of Energy; 2024.

13. Brandt KL, Martinez-Valencia L, Wolcott MP: **Cumulative impact of federal and state policy on minimum selling price of sustainable aviation fuel**. *Front Energy Res* 2022, **10**:828789.

14. Scown CD, Baral NR, Yang M, Vora N, Huntington T: **Technoeconomic analysis for biofuels and bioproducts**. *Curr Opin Biotechnol* 2021, **67**:58-64.

15. Kim H, Baek S, Won W: **Integrative technical, economic, and**
• **environmental sustainability analysis for the development process of biomass-derived 2,5-furandicarboxylic acid**. *Renew Sustain Energy Rev* 2022, **157**:112059.
The above paper performed a TEA of FDCA bioproduct via a novel process design and calculated the results using just the n^{th} plant assumptions. While the results of the paper identified feedstock costs and reaction specifications to be the main cost drivers, the scope of the paper did not include TEA for FOAK/pioneer plant version of the pathway.

16. Dutta A, Talmadge M, Hensley J, Worley M, Dudgeon D, Barton D, Groenendijk P, Ferrari D, Stears B, Searcy E, *et al*.: **Techno-economics for conversion of lignocellulosic biomass to ethanol by indirect gasification and mixed alcohol synthesis**. *Environ Prog Sustain Energy* 2012, **31**:182-190.

17. S Jones, P Meyer, L Snowden-Swan, A Padmaperuma, E Tan, A Dutta, J Jacobson, K Cafferty : Process Design and Economics for the Conversion of Lignocellulosic Biomass to Hydrocarbon Fuels: Fast Pyrolysis and Hydrotreating Bio-Oil Pathway; 2013.

18. Tan EC, Talmadge M, Dutta A, Hensley J, Snowden-Swan LJ, Humbird D, Schaidle J, Biddy M: **Conceptual process design and economics for the production of high-octane gasoline blendstock via indirect liquefaction of biomass through methanol/dimethyl ether intermediates**. *Biofuels Bioprod Bioref* 2016, **10**:17-35.

19. RE Davis, NJ Grundl, L Tao, MJ Biddy, EC Tan, GT Beckham, D Humbird, DN Thompson, MS Roni : Process Design and Economics for the Conversion of Lignocellulosic Biomass to Hydrocarbon Fuels and Coproducts: 2018 Biochemical Design Case Update; Biochemical Deconstruction and Conversion of Biomass to Fuels and Products via Integrated Biorefinery Pathways; 2018.

20. Cruce JR, Beattie A, Chen P, Quiroz D, Somers M, Compton S, DeRose K, Beckstrom B, Quinn JC: **Driving toward sustainable algal fuels: a harmonization of techno-economic and life cycle assessments**. *Algal Res* 2021, **54**:102169.

21. RM Swanson, A Platon, JA Satrio, RC Brown, Hsu DD : Techno-Economic Analysis of Biofuels Production Based on Gasification; 2010.

22. Kazi FK, Fortman JA, Anex RP, Hsu DD, Aden A, Dutta A, Kothandaraman G: **Techno-economic comparison of process technologies for biochemical ethanol production from corn stover**. *Fuel* 2010, **89**:S20-S28.

23. D Humbird, R Davis, L Tao, C Kinchin, D Hsu, A Aden, P Schoen, J Lukas, B Olthof, M Worley, *et al.* **Process Design and Economics for Biochemical Conversion of Lignocellulosic Biomass to Ethanol: Dilute-Acid Pretreatment and Enzymatic Hydrolysis of Corn Stover;** 2011.

24. Merrow EW, Phillips KE, Myers CW: **Understanding Cost Growth and Performance Shortfalls in Pioneer Process Plants**. Rand; 1981.

25. Horvath RE: **Pioneer Plants Study User's Manual**. Rand; 1983.

26. Cervi WR, Lamparelli RAC, Gallo BC, De Oliveira Bordonal R, Seabra JEA, Junginger M, Van Der Hilst F: **Mapping the environmental and techno-economic potential of biojet fuel production from biomass residues in Brazil**. *Biofuels Bioprod Bioref* 2021, **15**:282-304.

27. Mukherjee A, Bruijnincx P, Junginger M: **Techno-economic**
• **competitiveness of renewable fuel alternatives in the marine sector**. *Renew Sustain Energy Rev* 2023, **174**:113127.
The above is a recent TEA study that compared the technoeconomic viability of four different green fuels for the marine sector. This paper used the RAND method to estimate the costs for each of the e-fuel and biofuel pathways' pioneer plant costs by first calculating the TEA results using the n^{th} plant assumptions.

28. Huang K, Brentzel ZJ, Barnett KJ, Dumesic JA, Huber GW, Maravelias CT: **Conversion of furfural to 1,5-pentanediol: process synthesis and analysis**. *ACS Sustain Chem Eng* 2017, **5**:4699-4706.

29. MM Wright, JA Satrio, RC Brown, DE Daugaard, D Hsu. **Techno-economic analysis of biomass fast pyrolysis to transportation fuels**, 2010. Doi:10.2172/993332.

30. Hess RW, Merrow EW, Pei RY: **An Application of the Pioneer Plants Study Methodology to a First-of-a-Kind MHD Central Station**. RAND; 1987.

31. Morrison GM, Witcover J, Parker NC, Fulton L: **Three routes forward for biofuels: incremental, leapfrog, and transitional**. *Energy Policy* 2016, **88**:64-73.

32. Rojas-Michaga MF, Michailos S, Cardozo E, Akram M, Hughes KJ, Ingham D, Pourkashanian M: **Sustainable aviation fuel (SAF) production through power-to-liquid (PtL): a combined techno-economic and life cycle assessment**. *Energy Convers Manag* 2023, **292**:117427.

33. Kreutz TG, Larson ED, Elsido C, Martelli E, Greig C, Williams RH: **Techno-economic prospects for producing Fischer-Tropsch jet fuel and electricity from lignite and woody biomass with CO_2 capture for EOR**. *Appl Energy* 2020, **279**:115841.

34. Tsagkari M, Couturier J, Kokossis A, Dubois J: **Early-stage capital cost estimation of biorefinery processes: a comparative study of heuristic techniques**. *ChemSusChem* 2016, **9**:2284-2297.

35. P Kobos, T Drennen, A Outkin, E Webb, S Paap, S Wiryadinata : **Techno-Economic Analysis: Best Practices and Assessment Tools**; 2020.

36. •• Konzock O, Nielsen J: **TRYing to evaluate production costs in microbial biotechnology**. *Trends Biotechnol* 2024, **42**:1339-1347.
A recent publication that highlights the use of TRY metrics (Titers, Rate, and Yield) that play a significant role in the TEA results of microbial bioprocesses and therefore are useful metrics for the comparison of different pathways.

37. Chinery L, Allaouidine C, Tomazzini A, Larson M, Gülmezoglu AM: **Cost of goods sold analysis and recommendations to reduce costs of co-packaged mifepristone–misoprostol for medical abortion**. *Reprod Health* 2020, **17**:171.

38. •• Hoey M, Clark R, Webb E, Lynd L: **Scale sensitivity of ethanol production via consolidated bioprocessing with consideration of feedstock cost**. *Biofuels Bioprod Bioref* 2024, **19**:9-17, https://doi.org/10.1002/bbb.2691.
A recent publication that studied the impacts of production scale, stover yield, participation rate, and price incentives on the minimum selling price of ethanol via different production pathways. This paper highlighted the use of payback period as a TEA metric to measure the economic viability of pathways.

39. Ferdous J, Bensebaa F, Pelletier N: **Integration of LCA, TEA, process simulation and optimization: a systematic review of current practices and scope to propose a framework for pulse processing pathways**. *J Clean Prod* 2023, **402**:136804.

40. • Humbird D, Dutta A, Subramaniam H, Mendez J: **Design, scaling and cost evaluations of circulating fluidized-bed systems for biomass pyrolysis**. *Biofuels Bioprod Bioref* 2023, **17**:803-816.
A TEA study that applied process industry software to estimate the capital costs of purchased equipment that make up circulating fluidized-bed systems for biomass pyrolysis. This study highlights the need for process specific estimation methods for capital costs of equipment for bioprocesses and is relevant for FOAK-based TEA studies.