Scaling Up Bioenergy Technologies

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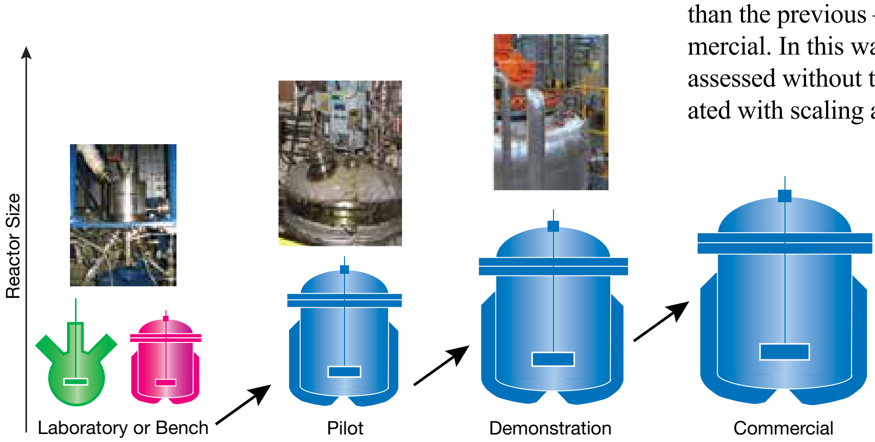
The stage-gate technique used for traditional chemical processes must be modified for bioenergy technologies. Follow these recommendations to minimize risk and maximize success.

A stage-gate method can be used to scale up biofuels processes, such as fermentation, thermochemical pyrolysis or gasification, and catalytic and enzymatic processes that convert biomass to ethanol and other fuels and products. However, the approach developed for traditional chemical process industries (CPI) projects must be modified to account for challenges related to processing the fluids and handling the solids in bioenergy processes. Because of these challenges, the scaling factors in going from one scale to the next (*i.e.*, laboratory to pilot to demonstration to commercial) are an order of magnitude lower for bioenergy processes than for similar CPI processes.



▲ **Figure 1.** A new technology is scaled up through progressively larger-scale stages. The differences between biofuels processes and conventional CPI technologies require modifications to the stage-gate process.

This article discusses the stage-gate approach for scaling up biofuels technologies, emphasizing how this approach differs from the traditional stage-gate process used in the CPI. It identifies the most common challenges encountered when scaling a biofuel process and offers recommendations for addressing these challenges. Finally, the article provides estimates of scaling factors for biofuels processes and compares them to the scaling factors for traditional CPI processes.

Technology stage gates

The stage-gate process (Figure 1) divides the scale-up of a technology into stages, each successively larger in scale than the previous — laboratory, pilot, demonstration, commercial. In this way, the viability of the technology can be assessed without taking on the large financial risks associated with scaling a technology directly from the lab scale to the commercial scale.

Lab scale. Equipment and systems used in the lab are important early-stage tools for assessing a new biofuels technology. Such systems are highly automated and customized for the application, and are a precursor to larger pilot- and demonstration-scale plants. Figure 2 shows a lab-scale ebullated-bed reactor for continuously upgrading bio-oil.

Laboratories typically assess continuous-stirred tank reactor (CSTR) or autoclave processes in batch equipment,

▲ **Figure 2.** This lab-scale ebullated-bed reactor with internal recirculation is used to upgrade bio-based oil. Photo courtesy of Zeton.

and assess fixed- or fluidized-bed reactors in once-through systems. In batch-autoclave applications, researchers manually load solids into the vessel, close the vessel, and run the system at the desired temperature and pressure for a specific residence time. In once-through fixed- or fluidized-bed reactor applications, the feed is added and the product removed continuously. Researchers can then plot reaction yield and selectivity for a range of operating conditions. Reactor volumes in lab-scale systems are typically less than 1,000 mL.

A frequent challenge for bioenergy projects at the lab scale is reliable solids feeding, especially at the high feed pressures required by some processes. To address this, researchers should test prototype feed systems with a representative

Bioenergy vs. Chemical Processes

The differences between traditional CPI processes and bioenergy technologies have several important implications:

- Bioenergy demonstration plants are often smaller, with a much lower nameplate capacity, than demonstration plants for traditional CPI processes.
- Bioenergy plants may have limited turndown, because the flow of solids is not as easily controlled as the flow of gases or liquids.
- It might be possible to skip a development step for a traditional CPI process, if there is sufficient confidence in the lab and pilot data. This is rarely the case for bioenergy processes, where the scale-up work is often being carried out for the first time.
- The overall development cycles are longer for bioenergy processes than for traditional CPI processes.
- The commissioning period for bioenergy plants is also longer (up to twice as long) than for traditional CPI plants of similar scale.

▲ **Figure 3.** Solids handling should be carefully considered as early as possible in the development of biofuels technologies. A lab-scale (100-g/hr) pressurized feed system is shown here. Photo courtesy of Zeton.

biomass sample. The custom-designed lab-scale solids feeder in Figure 3 is capable of feeding biomass (wood) at a nominal rate of 100 g/hr at pressures up to 700 psi.

Pilot scale. Pilot plants provide the first window into continuous processing, and often incorporate unreacted feed or product recycle systems. Figure 4 shows a traditional CPI pilot plant that has been modified to include continuous biomass feeding equipment for a biomass catalytic cracking application.

Catalyst performance tests are carried out to determine, or confirm, yield and selectivity, and the lifetime of the catalyst is measured under varying operating conditions. Reactor size at the pilot-plant scale typically ranges between 1 L and 100 L.

For predominantly batch processes in which solids handling is not a major concern, scale-up from a pilot plant directly to a commercial plant may be possible. Continuous processes, such as those employing fixed- or fluidized-bed reactors, typically require scale-up from pilot to demonstration scale.

Demonstration scale. Demonstration plants differ from pilot plants in that the equipment and process flow much more closely resemble those of commercial-scale operations. Extended operating runs permit catalyst lifetime studies over a longer period of time, and significant quantities of final product can be produced for market testing. The demonstration-plant stage is the final technology hurdle before commercialization.

Demonstration plants can have significantly higher capital and operating costs than pilot plants, and are typically not employed until the process technology is already well developed. They are often installed at the site of the future commercial plant to take advantage of existing infrastructure, utilities, operating permits, and zoning provisions.

While reactor volumes in traditional catalytic processes are typically 100–1,000 L at the demonstration scale, they are much larger for biological processes (10,000–40,000 L). This is because reaction rates and yields are much lower in biological systems than in catalytic systems. The demonstration plant in Figure 5 features a 40,000-L bioreactor for the production of cellulosic ethanol.

For continuous bioenergy and biofuels processes involving solids handling, the demonstration plant is an essential risk-mitigation step. The inherent risk in scaling continuous biofuels and bioenergy processes directly to the commercial scale based on lab or pilot data is, in most cases, too large to be given serious consideration. Technology developers need to go through the demonstration scale to prove to the market and investors that their technology meets performance expectations and is ready for commercialization.

Challenges in bioenergy process development

While the recommended approach for scaling bioenergy technologies follows steps similar to those for scaling chemical processes, several factors must be carefully considered. Table 1 lists the most common challenges.

Solids handling is much more difficult to scale than liquid and gas handling. Systems for handling solids are commonly constrained by geometry and physical limits. For example, the smallest outlet through which a material can easily flow may be much larger than the process lines in a pilot plant.

Solids-handling applications are also less forgiving than liquid and gas applications. Minor changes, such as changes in moisture content or particle size, can significantly impact solids-handling systems. It is not uncommon for a system to work well for one material and not work at all for another material with similar properties.

Designing a feed system to handle corn stover and pine sawdust illustrates this challenge. Even if their particles are similarly sized, the flowability of these two materials is noticeably different. Pine sawdust has a more uniform particle shape, whereas corn stover consists of long fibers that have a higher propensity for arching. In small-diameter feed screws, the corn stover fibers tend to bind together, which requires a higher mechanical torque. This will likely require the use of multiple screw feeders in custom-machined sizes with variable feed rates tailored for different types of biomass of varying properties.

Solids fluidization is a challenge in pilot-scale reactors. At smaller reactor diameters, wall effects are larger and the propensity for slugging is greater. In some cases, the minimum safe diameter for a reactor dictates the total output of the plant. Thus, it is important to use a system that allows for careful control of the bed particle size, shape, and hardness, and to develop methods to mitigate attrition, such as continuous replacement of bed material.

Leakage may be a concern in high-pressure applications, especially those handling hazardous process gases (*e.g.,* synthesis gas). Continuous processes require feed systems that continuously introduce biomass into the reactor, and all of these components have an inherent leakage rate. The allowance for leakage must be carefully considered at the early stages of the project, as it can significantly affect the capital and operating costs of the commercial plant.

Biomass-handling plants may have limited turndown, because the flow of solids is not as easily controlled as the flow of liquids or gases. For example, a cyclone separator achieves maximum efficiency at a very specific flowrate, and as the volumetric flowrate decreases, the particle-separation efficiency also decreases.

▲ **Figure 4.** A traditional CPI pilot plant has been modified to include a continuous biomass feed system. Photo courtesy of Zeton.

▲ **Figure 5.** Coskata's fully integrated demonstration-scale facility was a critical step in the development and demonstration of the company's feedstock-flexible technology. Photo courtesy of Coskata, Inc.

Table 1. Common challenges encountered in scaling up biofuels technologies.
Varying physical and chemical properties of solid biomass feeds
Continuous pressurized solids feeding and handling, including collection of solids byproducts and removal of ash and char
Condensing bio-oil vapors and associated formation of aerosol
Hot-gas filtering in thermochemical-conversion processes
Bio-oil upgrading, stability, and varying physical and chemical properties of bio-oil during processing
High-temperature solids circulation and processing
Operating small-diameter fluidized beds with low feed rates at the lab scale
Tar formation and removal in gasification processes

Recommendations

The success of a bioenergy scale-up project will largely depend on how these challenges are addressed. Here are several suggestions for dealing with them:

• Line metal surfaces with a refractory material to handle the high operating temperatures typically seen in thermochemical conversion processes.

• Purge instrument impulse lines to prevent solids plugging, and use gas pulsing to clear filter elements.

• Develop prototype micro- and lab-scale solids-feeding systems using actual biomass feed samples.

• Use multiple screw feeders in custom-machined sizes with variable feedrates that can handle different biomass feeds with varying properties.

• Use specially designed mechanical devices that eliminate tar build-up to prevent plugging.

• Use direct-contact circulating scrubbing systems for bio-oil condensation in thermochemical processes to minimize aerosol formation (rather than using indirect condensation, which is often incapable of condensing bio-oil vapors).

Scaling factors

The scaling factor for any particular process is highly specific to the technology under investigation and management's level of comfort with the scale-up risk. Table 2 compares scaling factors for bioenergy projects with the scaling factors often used for more traditional CPI liquid- and gas-based processes. These factors are based on Zeton's experience in scaling many different bioenergy and traditional CPI technologies.

The typical scaling factors for bioenergy processes are an order of magnitude lower, or more conservative, than those for similar CPI processes. This is a direct result of the inherent challenges with biomass processing, and the fact that there is little published data, and a lack of experience in general, related to the scale-up of advanced bioenergy processes.

Table 2. Scaling factors for biofuels processes are typically lower than those for traditional CPI technologies.

Scale	Traditional CPI	Biofuels Processes
Lab/Bench	0.001–0.1 (1–10 mL/min)	0.01–0.1 (1–10 g/hr)
Pilot	1 (1–5 L/hr)	1 (1–5 kg/hr)
Demonstration	100–1,000* (5–100 bbl/day)	10–100† (1–5 m.t./hr)
Commercial	10,000–30,000 (30,000–100,000 bbl/day)	1,000–5,000 (200–1,000+ m.t./hr)

* For well-understood and established processes for which a commercial plant already exists, data from the pilot plant can be correlated directly to the commercial scale, bypassing the demonstration plant stage.

† The demonstration plant is an essential risk-mitigation step for bioenergy and biofuels projects involving solid-biomass handling, as well as for more traditional CPI gas and liquid processes involving novel or unproven technologies.

Closing thoughts

Consider these key tips for scaling up a bioenergy technology:

First, in planning the timeframe to develop the technology through the pilot and demonstration stages, remember that the start-up and commissioning time for such plants will be longer than for traditional CPI plants due to the extra time required to fine-tune the solids-handling system.

Second, the scaling factors used from lab through pilot and demonstration to commercial scale are an order of magnitude lower for bioenergy plants than for traditional CPI processes due to the challenges associated with solids handling.

Third, it is important to answer questions regarding the intellectual property (IP) involved in the bioenergy technology you are scaling up. Partnering with suppliers with a proven track record of success in similar applications will shorten the technology scale-up cycle, while also, with appropriate foresight, protecting and strengthening your company's IP position. CEP

Additional Resources

Cort, J. B., *et al.*, "Minimize Scale-Up Risk," *Chemical Engineering Progress*, **104** (3), pp. 39–49 (Mar. 2010).

Edwards, D., "Scaling Up Step by Step," *Biofuels International*, **9** (6), pp. 44–46 (Nov. 2012).

Szabo, P., "Follow this Process Development Path," *Chemical Engineering Progress*, **107** (12), pp. 24–27 (Dec. 2013).

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