Distributed Production of Biobased Products with Biomass Processing Modules

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Opportunity

The United State's natural resource base of soils and climate has made it one of world's leading producers of food crops. Its resource base also has the potential to grow large quantities of biomass for the manufacture of biobased products, as demonstrated by the fact that the U.S. is the world's leading manufacturer of grain-based ethanol. To fully develop this potential, manufacturing technologies will have to be developed that (1) utilize cellulosic feedstocks, like wood, cornstover, and switchgrass, and (2) allow for distributed processing of these feedstocks into biofuels. Currently, the manufacture of biofuels depends too heavily on crops that are also used in food production. Although the national resource base of cellulosic biomass is estimated to be in excess of one billion tons annually, it is bulky and highly distributed across the countryside, complicating its collection and delivery to processing facilities. Thus, advanced biofuels production would benefit from technologies that could be widely deployed at relatively small scales, processing as little as 50-200 tons per day (tpd) compared to today's corn ethanol plants (2,000 tpd) and petroleum refineries (>10,000 tpd).

Challenge

The challenge to distributed production is that the unit cost of product manufacture typically increases as plant size decreases. This arises from "economies of scale": the amount of material and labor required to construct a plant and the number of employees required to run it do not increase linearly with plant output. The unit cost of plant operations, excluding the cost of feedstocks, can be expressed by the power law relationship:

$$C_P/M = \left(C_{Po}/M_o\right) M^{n-1} \tag{1}$$

where C_P is the cost of plant operations for a facility of capacity M, n is a power law exponent less than unity, and C_{Po} and M_o, are the cost of plant operations and capacity, respectively, of a baseline manufacturing facility. This exponent is often assumed to be 0.6 (the "sixth-tenth" rule) although it can exceed 0.9 for very large energy production facilities.[1] Thus, the unit cost of plant operations, C_P/M, declines as the plant is made larger (where n-1 is a negative number). This indicates that manufacturing plants should be built as large as possible, which explains the enormous scale of petroleum refineries and modern coal-fired power plants.

The analysis is more complicated when the cost of delivered feedstock is a major cost of production, as occurs for biomass processing, which can dramatically influence the optimal size of a plant. The cost of delivered feedstock has two components: the cost of feedstock, C_F, at the well head or mine mouth (for fossil fuel feedstocks) or farm gate (for biomass feedstocks) and the cost to deliver the feedstock, C_D, to the production facility. In general, C_F increases linearly with the capacity of the production facility whereas C_D depends upon the nature of the feedstock. For fossil fuel feedstocks, delivered from a single mine head or a highly integrated pipeline network, this cost is approximately linear with plant capacity. However, for biomass resources feedstock supply is widely distributed. Since the amount of biomass increases as the square of distance from the plant, the cost of delivery increases with plant capacity to the power of 1.5.[2]

The *total* unit cost of manufacturing a biobased product, C_T/M, including plant operating costs, feedstock costs, and feedstock delivery costs can be expressed as:[3]

$$C_T/_M = \left(C_{Po}/_{M_o^n}\right) M^{n-1} + \left(C_{Do}/_{M_o^m}\right) M^{m-1} + \left(C_{Fo}/_{M_o}\right) \qquad (2)$$

where C_{FO} and C_{DO} are the feedstock costs and feedstock delivery costs, respectively, for a baseline production facility and the exponent m is equal to 1.5 or possibly as large as 1.5 for scarce biomass resources. Since n-1 is less than zero and m-1 is greater than zero, the first term on the right hand side of Eqn. 3 decreases with plant capacity while the second term increases with plant capacity. Thus, there is an *optimal* plant size for the lowest unit cost of biobased product, as illustrated in Figure 1 for biofuels production. Surprisingly, the optimal plant sizes even for cellulosic biofuels are several hundred million gallons. It would appear that feedstock delivery costs are not so drastically high as to encourage the construction of relatively small-scale plants. However, the high cost of capital and the volatility of petroleum prices conspire to discourage investment in the construction of such large-scale biobased manufacturing facilities: few investors can afford the risk that a brief downward fluctuation in petroleum prices would force them to shutter a billion dollar biobased manufacturing facility.

Potential Solution

The potential solution to this quandary is to break the "tyranny of the economies of scale," which means driving the power law exponent n in Eqn. 2 toward unity, in which case there is no optimum plant size. In this case, plants could be built at a scale that matches prevailing financial risk. A biobased enterprise could start small and expand as the market developed without fear that a competitor would subsequently build a slightly larger plant in order to secure a lower unit cost of production.

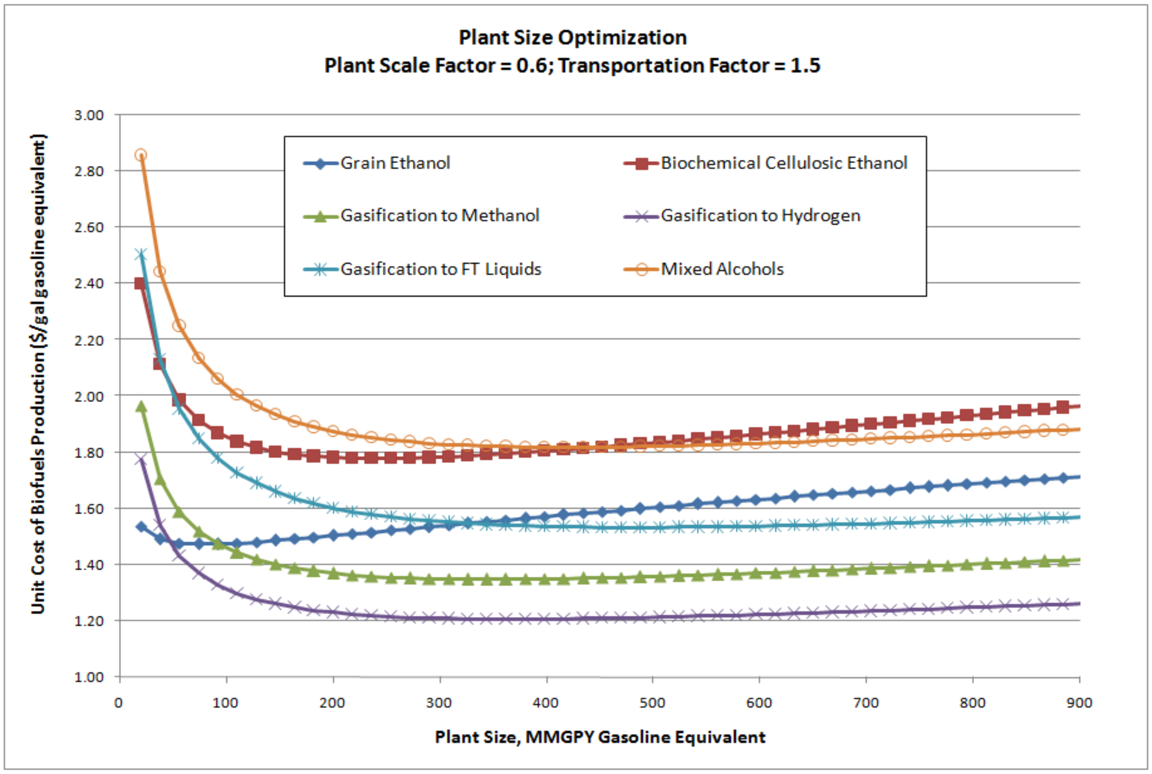

Figure 1. Optimal plant size for different kinds of biofuels production facilities (adapted from Reference 3).

Achieving a linear scaling law requires both changes in how advanced biobased manufacturing plants are built and how they are operated. Currently, production facilities are custom designed and field constructed over many months or even years. Once completed, the number of staff needed to operate them is not strongly dependent upon plant size. Both factors favor large-scale facilities.

Replacing field construction with mass production of “biomass processing modules” in highly automated factories would advantage small-scale biofuels production facilities. These modules would be shipped to the plant site and rapidly field-assembled into a complete plant in a matter of days or a few weeks. This would capture the same economies of scale inherent in mass production of automobiles and other consumer products.

Small-scale biofuels production facilities, once constructed, could gain the same economies of scale in staffing as large plants through expanded use of automated sensors and controls and remote system management. Whereas a conventional small plant needs its own dedicated staff that resemble in make-up and number the staff of a large plant, advanced biobased manufacturing based on the distributed production model would have one team simultaneously managing several small plants.

Within the electric power industry, linear scaling is already achieved in the manufacture of photovoltaic (PV) panels and wind turbines in factories. These are field assembled into renewable power arrays that can be managed by a relatively small staff. A similar concept is envisioned for conversion of biomass into biofuels.

There is good reason why the solar power and wind power industries adopted mass production and distributed deployment ahead of the biofuels industry: they had no good alternative. Although the energy fluxes of sunlight and wind in the biosphere are somewhat higher than for biomass, the latter can be collected and aggregated before conversion into other energy forms. Sunlight and wind are not so readily channeled before conversion. Furthermore, the devices that convert this energy into electricity are complex to construct, requiring the controlled environment of a factory.

The operation of PV arrays and wind turbines also naturally suits them for deployment as small-scale, distributed units operated as networked systems. Their output is electricity, which readily lends itself to automated sensing, control, and even distribution to markets. In contrast, the manufacture of biofuels involves fluxes of solids, liquids, and gases as well as electricity and heat. The management of these fluxes requires more complex sensing and control systems.

Furthermore, whereas heat plays a secondary role in the overall energy flows of PV panels and wind devices, it is a primary form of energy in many biomass processing technologies. This is an important distinction because heat flow is strongly dependent on the scale of equipment. Success in distributed biofuels production will require careful attention to heat flows, especially for high temperature processes.

References

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