PERSPECTIVE

Challenges in Scaling Up Biofuels Infrastructure

Tom L. Richard

Rapid growth in demand for lignocellulosic bioenergy will require major changes in supply chain infrastructure. Even with densification and preprocessing, transport volumes by mid-century are likely to exceed the combined capacity of current agricultural and energy supply chains, including grain, petroleum, and coal. Efficient supply chains can be achieved through decentralized conversion processes that facilitate local sourcing, satellite preprocessing and densification for long-distance transport, and business models that reward biomass growers both nearby and afar. Integrated systems that are cost-effective and energy-efficient will require new ways of thinking about agriculture, energy infrastructure, and rural economic development. Implementing these integrated systems will require innovation and investment in novel technologies, efficient value chains, and socioeconomic and policy frameworks; all are needed to support an expanded biofuels infrastructure that can meet the challenges of scale.

The next few decades will require massive growth of the bioenergy industry to address societal demands to reduce net carbon emissions. This is particularly true for liquid transportation fuels, where other renewable alternatives to biofuels appear decades away, especially for truck, marine, and aviation fuels. But even for electricity and power, the growth potential of other renewables and nuclear power appears limited by high cost, technology barriers, and/or resource constraints. With estimates of bioenergy potential ranging from just under 10% to more than 60% of world primary energy (*1–4*), biomass seems poised to provide a major alternative to fossil fuels. As a point of reference for considering future biomass infrastructure needs, the International Energy Agency (IEA) (*4*) estimates that a 50% reduction in greenhouse gas emissions by 2050 will require a factor of 4 increase in bioenergy production, to 150 EJ/year (1 EJ = 10^{18} J), providing more than 20% of world primary energy.

With both agronomic and societal concerns about further increases in the use of grains and oilseeds for biofuels, almost all of this increased bioenergy will likely come from lignocellulosic feedstocks: dedicated energy crops, crop residues, forests and organic wastes. These materials have considerably lower bulk densities than grains, resulting in significant logistical challenges. The transportation fraction of the energy required to grow and deliver energy crops to a biorefinery is only 3 to 5% for grains and oilseeds, but increases to 7 to 26% for lignocellulosic crops such as switchgrass, miscanthus, and other forages and crop residues (*5–7*). These transportation costs represent a diseconomy of scale for lignocellulosic biofuels that contrasts with, and at large scales can overwhelm, the economies of scale associated with advanced conversion technologies.

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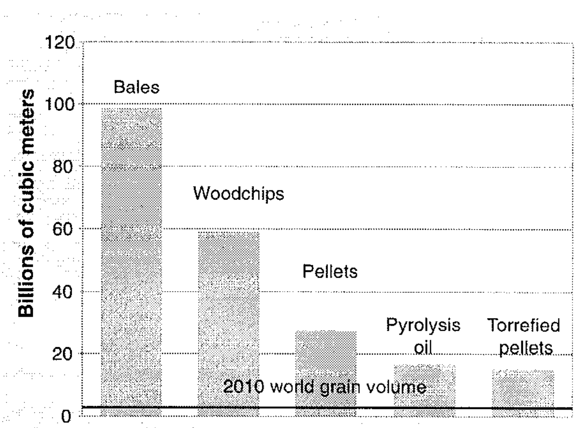

Fig. 1. Global biomass volumes required to achieve a 50% reduction in greenhouse gas emissions by 2050. A wide range of densification options are possible, but even the most effective will still require several times the biomass-handling capacity that the commodity grain system uses today.

To reach the IEA 2050 target of 150 EJ/year, primary energy from biomass would require 15 billion metric tonnes [i.e., megagrams (Mg)] of biomass annually, assuming 60% conversion efficiency (*4*, *7*) and a biomass energy content of 17 MJ/kg dry matter (*8*). A typical dry bulk density of grasses and crop residues is about 70 kg/m^3 when harvested, so without compaction the shipping volume of these 15 billion Mg would require more than 200 billion cubic meters (bcm). At baled grass and woodchip densities of 150 and 225 kg/m^3 (*8–10*), this transport volume would be 100 or 60 bcm, respectively (Fig. 1). Using reported energy densities of pellets, pyrolysis oil, and torrefied pellets (*6*), these densified products would require 28, 17, and 15 bcm of transport capacity, respectively.

To gain some perspective on the quantities involved, consider the volumes of related commodities currently being managed. For agricultural commodities, the sum of rice, wheat, soybeans, maize, and other coarse grains and oilseeds will approach 2 billion tons in 2010, with a total volume of 2.75 bcm (*11*). Current global volumes of energy commodities are somewhat larger, with 6.2 bcm of coal and 5.7 bcm of oil transported in 2008 (*12*). Thus, the combination of expected growth in energy demand and the lower density of biomass imply that by 2050, biomass transport volumes will be greater than the current capacity of the entire energy and agricultural commodity infrastructure.

These volumes imply a major growth opportunity for manufacturers of biomass-handling and transport equipment, but also a major stress on the transportation infrastructure, especially in rural regions around the world. If managed poorly, this additional traffic could degrade rural roadways and increase safety concerns. But increased demand for biomass could also provide a strong incentive to improve rural transportation infrastructure, facilitating agricultural and economic development in concert with renewable energy.

The size and efficiency of bioenergy conversion facilities will determine how far these huge volumes of biomass and biofuel will need to travel, and thus transportation's contribution to the energy, economic, and environmental impacts of biomass use. At a community scale, biomass energy can be converted in combined heat and power (CHP) systems producing 1 to 30 MW at efficiencies of 80% or more (*4*). At 80% efficiency, 30 MW of useful energy would require 150 Mg/day of biomass, or roughly five semi-trailer truckloads per day. These decentralized systems have the potential to source feedstock locally with minimum infrastructure costs. In contrast, cellulosic biofuel refineries are expected to achieve economies of scale at 200 to 1000 megaliters (ML) per year (*7*, *13*, *14*). Above this size range, the marginal cost of biomass transport can become greater than the marginal savings of larger biorefinery equipment on a per-unit basis (*13*). At the lower end of this range, feedstock needs would be equivalent to those of a 300-MW power plant, and a single biorefinery would require 50 trucks to deliver the 1600 Mg of biomass consumed each day. At the high end of this range, with 250 trucks per day, one truck would be unloading every 5 min around the clock.

These larger biorefineries and their expected volumes of flow will require a shift to a large-scale integrated transportation infrastructure if biomass is going to be a competitive energy resource at the scale of coal and petroleum. For longer distances, rail, ship, and pipeline transport of biomass become increasingly attractive. These represent proven, efficient solutions to transporting large volumes long distances and have been analyzed for a range of biomass types and preprocessing strategies (*6*, *15*–*17*).

Scale issues can also be addressed through synergistic combinations of biomass with other energy resources. Existing coal-fired power plants and petroleum refineries can incorporate properly formatted biomass as an alternative feedstock (*18*–*20*). Local sourcing of that biomass can thus reduce the diseconomies of scale associated with hauling distance while achieving economies of scale in conversion.

Other innovative strategies may help minimize the cost and maximize the value of biomass feedstock supply chains. By moving to a uniform format of particle size and density at or close to the harvest location, diverse biomass feedstocks could be handled by common equipment throughout the commodity chain (*9*). Pretreatment could be performed during transport and storage, as has been investigated for pipeline transport (*21*) and ensiled storage (*22*).

The transportation and logistics at the back end of a biofuel refinery must also be addressed. Ethanol is incompatible with the current fuel pipeline distribution system due to its corrosivity and its azeotrope with water, which can lead to pipe or tank failure and fuel contamination, respectively. That 200 ML/year biofuel plant would require 16 to 20 tanker trucks or railcars per day to move the fuel to market, increasing both traffic and costs (Fig. 2). These fuel distribution challenges are helping drive the interest in "drop-in" fuels that would be compatible with both the existing fuel distribution infrastructure as well as the vehicle fleet. Several such advanced biofuels are nearing commercialization, including butanol, Fischer-Tropsch fuels, and other bio-based gasoline and diesel equivalents. But regardless of the fuel product, massive investments in new pipe, rail, and highway infrastructure are needed to move those fuels from a new biorefinery network dispersed across the landscape. Both feedstock supply and fuel distribution logistics will influence the optimal size required for these biorefineries to achieve economies of scale (*23*).

In recent years several studies have evaluated alternative supply chain configurations to minimize overall feedstock delivery costs from regional to international scales (*6*, *9*, *24*–*30*). Several of these logistics models have identified critical points in the supply chain, where the relationships of distance and density conspire to increase transportation costs. A common feature in optimized high volume long distance biomass supply chains is a preprocessing stage that includes particle size reduction and densification, but can also include pretreatment of the biomass to facilitate both transport and downstream use. Depending on the technology, this preprocessing can be done on-farm or in community-scale satellite processing facilities (*9*).

Densification strategies include baling systems for grasses, crop residues, and forest trimmings as well as higher-density pellets and cubes (*31*–*34*) (see Fig. 1). Densification can be coupled with pretreatment processes that prepare the feedstock for downstream conversion. For biochemical conversion processes, the ammonia fiber expansion pretreatment process can produce a readily pelletized biofuel feedstock that can also be marketed as a highly digestible livestock feed (*35*). For combustion and thermochemical processes, torrefied pellets have a high energy density and become brittle, facilitating efficient combustion or gasification as well as cocombustion with coal at much higher blend rates than are possible for unprocessed biomass (*6*). Another thermochemical pretreatment prospect is pyrolysis, which produces a bio-crude oil. Although capital costs, oil stability, corrosivity, and deoxygenation remain challenges for pyrolysis (*6*), downstream conversion possibilities include gasification and blending with petroleum in conventional refineries. Pyrolysis also produces a biochar coproduct that can be used to improve soil quality, serving as a carrier for returning recovered nutrients to the soil. Interestingly, the economies of scale for most of these densification and preprocessing technologies plateau in the range of 20 to 80 MW thermal equivalent (*6*), similar to that of the decentralized CHP units previously described. Integrating these preprocessing operations with heat and electricity production could provide important synergies for both capital cost and operations.

Fig. 2. Truck transport of feedstock **(top)** and fuel **(bottom)**. Brazilian sugar cane factories operate as a plantation system, with monocultures of sugar cane surrounding each refinery. Most sugar cane production is within 100 km of Sao Paulo, Brazil's largest city and industrial base, so the markets for biofuels are relatively close. In the United States, by contrast, midwestern corn ethanol must travel by road and rail more than 1000 km to markets on the east and west coasts.

Economic analysis of both preprocessing and conversion systems highlights the importance of year-round operations, as it is difficult to amortize capital costs for facilities that are only used for a few months of the year (*6*, *13*). However, many biomass feedstocks have optimal harvest periods that may run for only a few weeks. There are likely other seasons during which harvesting should not occur due to weather or various ecosystem constraints. Livestock farmers have been facing a similar problem supplying forages to their 24/7/365 milk- and meat-producing animals for over a thousand years, and have developed effective wet (<70% dry matter) and dry (>80% dry matter) storage systems for grasses and crop residues (Fig. 3). Dry biomass is preferred for pellets, torrefaction, and downstream thermochemical processing, where the presence of water would reduce overall energy efficiency. Wet storage systems couple well with single-pass harvest systems to reduce harvesting and drying operations, can minimize soil contamination and dry matter losses, and can add value to some downstream processes (*10*, *22*). Seasonality constraints and storage requirements can be minimized by systems with the flexibility to process diverse feedstocks, which should be a consideration throughout the value chain from harvest to fuel conversion (*9*).

The amount of nearby land dedicated to energy crops will also greatly affect the costs of feedstock supply (*26*). Even short supply chains can substantially increase the cost of some biomass resources between the field and the biorefinery gate (*9*, *36*). As the scale of a biomass conversion facility increases, the advantages of maximizing the dedicated acreage near the facility, and thus minimizing feedstock transport distances, clearly increase.

The push-pull between economies of scale for conversion facilities and diseconomies of scale for feedstock supply chains suggests three distinct business models for biomass feedstock supply: independent local suppliers, large contiguous plantations, and regional or global commodity markets.

Independent local feedstock suppliers can work well for smaller biomass energy facilities, including combined heat and power plants that require a few truckloads of biomass each day or week. Such operations would have relatively short haul distances, little need for specialized equipment, and the extra expense required for densification would not be required. Local supply chains are currently common throughout the world, supplying everything from firewood for charcoal to waste oil for biodiesel.

A second model of biomass supply chains is the plantation approach, where a single company controls a large contiguous land area. Plantations have long provided concentrated production of agricultural and forest products for high volume processing and international markets. This strategy is being used today for bioenergy crops in many regions of the world, including sugar cane and soybeans in South America, oil palm in Malaysia, and canola in Ukraine. Most plantation systems have been structured so that the company needing the feedstock directly owns the land—an approach that historically has led to problems with land access, appropriation, and employee rights. However, secure but distributed land ownership patterns in many regions set the stage for alternative financial arrangements, including long-term contracts, profit sharing, and cooperative business financing that allow landowners to recoup their multi-year investments in perennial energy crops, while ensuring a concentrated feedstock supply for a processing facility. Any geographically concentrated feedstock supply system would do well to enhance the genetic diversity of its crops, including diverse varieties and multiple species, and have contingency plans that include backup suppliers to manage the risks of crop failure from weather or disease.

The third business model is the commodity biomass market, which would parallel the trading operations for other agricultural commodities (such as grains and livestock) as well as energy resources (such as petroleum and coal). In a commodity market there are clearly defined specifications for the product, which for biomass should include at a minimum levels of moisture, energy density, particle size, and the allowable content of certain minerals and contaminants. Aggregators can gather large quantities of the commodity, blend as needed to meet specifications, and then sell at market prices to buyers who are guaranteed a uniform feedstock. These aggregators can run the gamut from independent businesses to farmer cooperatives to large corporations. Any size is possible as long as the specification is met. Regardless of the scale of individual actors, a commodity system works most efficiently when transaction and transportation costs are low, so that distances between buyers and sellers have little impact on the price.

Although there is a great deal of interest from the biomass industry in building a commodity market, different feedstock specifications are relevant for combustion, biochemical processes, and thermochemical fuels. Biomass combustion is one bioenergy sector where formal specifications are already being developed to support established commodity supply chains (*37*, *38*). Biomass commodity specifications include explicit, measureable properties of the material as well as implicit value characteristics. The latter include sustainable production practices, which can be either voluntary or regulated and consider different geographical bounds (*39*–*41*). Although there is progress on several sustainability certification initiatives, there remains much uncertainty about where to set the bar, and the risks of unintended consequences are great.

The logistics of harvest, storage, processing, and transport weave a complex web of interactions that will require massive investments in research, development, demonstration and deployment to scale up biomass energy systems to meet societal goals. Although simulation models and commercial demonstrations help chart a course toward promising solutions, these still must be adapted to local feedstocks, infrastructure, and technology, as well as local socioeconomic contexts. Each facility, at every scale, will need to be supported by a cluster of complementary enterprises—a tightly choreographed supply chain that meets both local and global needs. These supply chains must also be value chains, striving to meet economic, environmental, and community goals. That balance requires an innovative, informed, and motivated citizenry—entrepreneurs, farmers, foresters, neighbors, and a host of new workers throughout the feedstock supply chain.

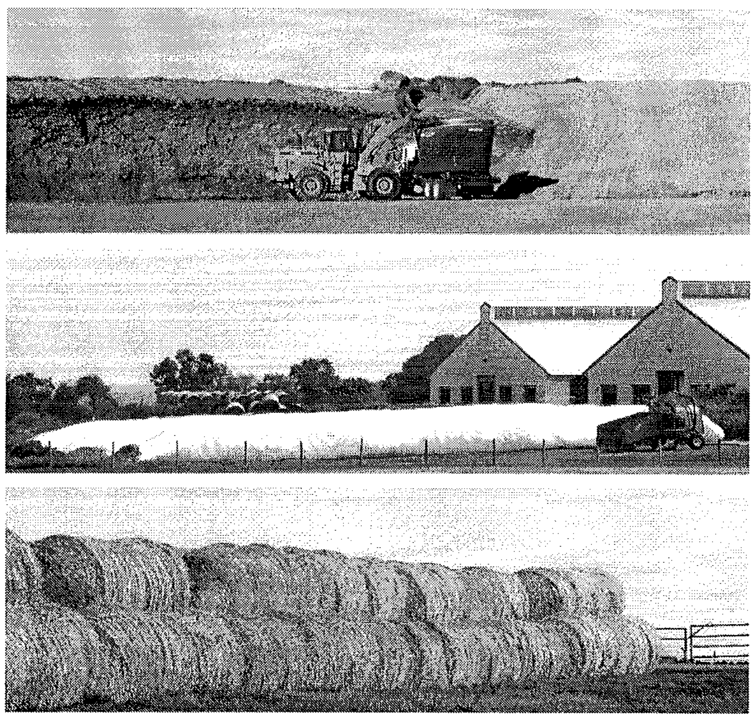

Fig. 3. Wet (**top** and **middle**) and dry (**bottom**) biomass storage configurations for lignocellulosic grasses. Because dry storage relies on low water activity to prevent microbial growth, it is most effective in arid regions. Wet storage, or ensilage, under anaerobic conditions encourages a natural acid fermentation that lowers pH and reduces microbial activity. Wet storage can keep dry matter losses below 5% for a full year, even in humid regions (*10*).

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PERSPECTIVE

An Outlook on Microalgal Biofuels

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Microalgae are considered one of the most promising feedstocks for biofuels. The productivity of these photosynthetic microorganisms in converting carbon dioxide into carbon-rich lipids, only a step or two away from biodiesel, greatly exceeds that of agricultural oleaginous crops, without competing for arable land. Worldwide, research and demonstration programs are being carried out to develop the technology needed to expand algal lipid production from a craft to a major industrial process. Although microalgae are not yet produced at large scale for bulk applications, recent advances—particularly in the methods of systems biology, genetic engineering, and biorefining—present opportunities to develop this process in a sustainable and economical way within the next 10 to 15 years.

The concept of using algae to make fuels was already being discussed 50 years ago (*1*), but a concerted effort began with the oil crisis in the 1970s. Large research programs in Japan and the United States focused on developing microalgal energy production systems. From 1978 to 1996, the U.S. Department of Energy's Office of Fuels Development funded a program to develop renewable transportation fuels from algae (*2*). The main focus of the program, known as the Aquatic Species Program (ASP), was the production of biodiesel from high-lipid-content algae grown in ponds, using waste CO_2 from coal-fired power plants. In Japan, the government financed a large research project entitled "Biological CO_2 Fixation and Utilization" from 1990 to 1999 (*3*). These programs yielded some successes—such as promising lipid production strains, open production systems (raceway ponds), and principles for photobioreactor design (the use of fiber optics to bring light inside the systems)—that are still the focus of research today, but none has proven economical on a large scale.

There have been several critical issues that combined have had a large influence on stimulating the resurgence of algal biofuels research. The world has experienced record crude oil prices, increasing energy demand, and environmental concerns that have pushed biofuels research in general to the fore. In the narrower context of

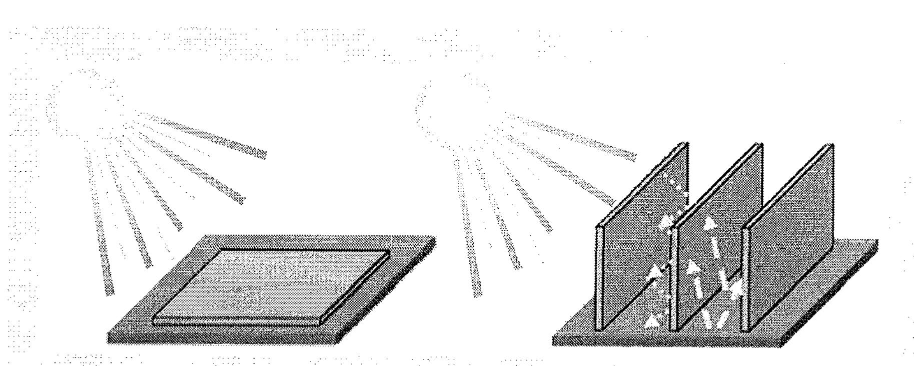

Fig. 1. The principle of light dilution. The light intensity (*I*) striking closely spaced vertical panels is much lower than the intensity striking a horizontal reactor on the same surface.

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