

Techno-economic assessment (TEA) of advanced biochemical and thermochemical biorefineries

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Abstract: This chapter covers techno-economic assessments (TEA) of advanced biochemical and thermochemical biorefineries. We discuss how governments, companies, and academic institutions are affecting the economic prospects of advanced biorefineries. The text describes their economic challenges and the various strategies being pursued to increase commercial adoption of advanced biorefineries: government incentives, facility scale-up, and technological innovation. Finally, we present an overall view of emerging trends in biorefinery TEAs with the intent of identifying key opportunities for improvement.

Key words: biorefinery techno-economic analysis (TEA), advanced biofuel incentives, biomass costs and logistics, thermochemical and biochemical conversion.

2.1 Introduction

The pace of biorefinery technology research and development is increasing, fueled by concerns over energy security and environmental impacts. Academic institutions and national laboratories are leading the assessment of promising biorefinery concepts. These assessments investigate concepts at various development stages – from laboratory research to plant-scale commercialization. In this chapter we summarize recent techno-economic analysis findings, discuss how policy influences biomass trade and industry subsidies, and describe the differences between national and regional biorefineries. Our concluding section contemplates the impacts of current challenges and emerging trends.

The term biorefinery encompasses different types of facilities that can convert biomass into valuable products (Brown, 2003). We define a biorefinery as an integrated facility capable of producing fuel, electricity, chemicals, and other types of bioproducts. This concept allows for the full

utilization of biomass compounds and the versatility to vary the product distribution. This concept builds upon the desire to replace every product derived from a barrel of crude oil. In addition to the main industrial building blocks, researchers envision biorefineries that could produce novel types of chemicals and polymers.

There are several biorefinery concepts at various stages of development and commercialization. Their future prospects depend on technological innovation and market conditions. Given the multiple steps required to convert biomass into marketable products, research breakthroughs along any of the conversion steps could accelerate the adoption of a given pathway. Similarly, market conditions could turn formerly unprofitable schemes into commercial successes. More than likely it will be a combination of technological and economic changes that lead the way to commercially-viable biorefineries. Thus, techno-economic assessments provide a unique perspective on current and future biorefinery technologies.

The United States and European governments have established guidelines and incentives to develop renewable fuels. Biorefineries that meet specific government conditions are eligible to receive financial incentives in the form of subsidies. Biorefinery subsidies are projected to increase from US\$66 billion today to almost US\$250 billion by 2035 (Anon., 2011).

Some biorefinery subsidies have expired in recent years without major impacts to industry growth, signaling the maturity of the biofuel market. However, government subsidy programs have begun to set strict requirements relating to direct and indirect lifecycle greenhouse gas emissions (GHG) on advanced biorefineries as a condition of participation. In order to meet these requirements, renewable energy companies are seeking novel approaches to convert a wider range of biomass into cleaner, cheaper bioproducts. This search requires the assessment of the technical and economic prospects of novel pathways. Therefore, governments are collaborating with academic institutions, national laboratories, and commercial enterprises.

The diffuse nature of biomass availability means that biorefinery scale-up will have wide area impacts on local, regional, and national scales. Although most biorefineries today are limited to capacities of about 100 million gallons (379 million liters) per year, process development and improved biomass logistics could lead to larger biorefineries that gather biomass from hundreds of square kilometers via truck, rail, or barge transport. These biorefineries will present novel, international case scenarios. Thus, there is interest in studying the challenges and opportunities for biorefineries in the global market from a TEA perspective.

The biomass industry presents a rapidly changing landscape with challenges and opportunities. Three recent trends have emerged as the result of faltering government support, sustained high petroleum prices,

and changing public opinions on biorenewables: the replacement of starch feedstocks with lignocellulosic biomass, interest in thermochemical pathways, and public and private investment in high-risk, high-reward alternatives.

Lignocellulosic biomass has historically proven difficult to convert into bioproducts with traditional biochemical approaches due to the biological recalcitrance of cellulose and antimicrobial properties of lignin. Developments in genetic and metabolic engineering have opened new pathways to convert hemicellulose into valuable products. These avenues range from enhancing biomass growth to developing bacteria strains capable of digesting formerly discarded or toxic parts of biomass crops.

Thermochemical research pathways have attracted recent attention due to their ability to inexpensively convert lignocellulosic feedstocks to energy-dense gases and liquids. Most of the recent development in the field has been on adapting conventional commercial processes (such as those employed by petroleum refineries) to handle biomass feedstocks and biobased intermediate products. However, there are growing efforts in the search for novel catalysts that can optimize the selectivity and yield of desired bioproducts. Finally, researchers have also proposed hybrid approaches that combine the strengths of the biochemical and thermochemical platforms (Brown, 2005).

There is growing commercial and political support for the development of high-risk, high-reward platforms such as microalgae-to-fuels, furan synthesis, and sugar-based hydrocarbons. Government-funded algae research was eliminated in the 1990s in favor of ethanol but has recently staged a resurgence due to concerns over land availability and GHG emissions.

2.2 Biorefinery economic assessment

Economic assessments are becoming important in the analysis of biorefinery concepts (Wright and Brown, 2011). This is due in part to the lack of commercial experience in establishing novel technologies that can convert alternative feedstock into products not commonly derived from renewable sources. Another factor is the recent volatility in oil prices yielding to the possibility of long-term financial viability of biorefinery projects. Finally, strong governmental support ensures that attractive processes receive financial support during development. These factors have resulted in an increase in the publication rates of biorefinery techno-economic studies.

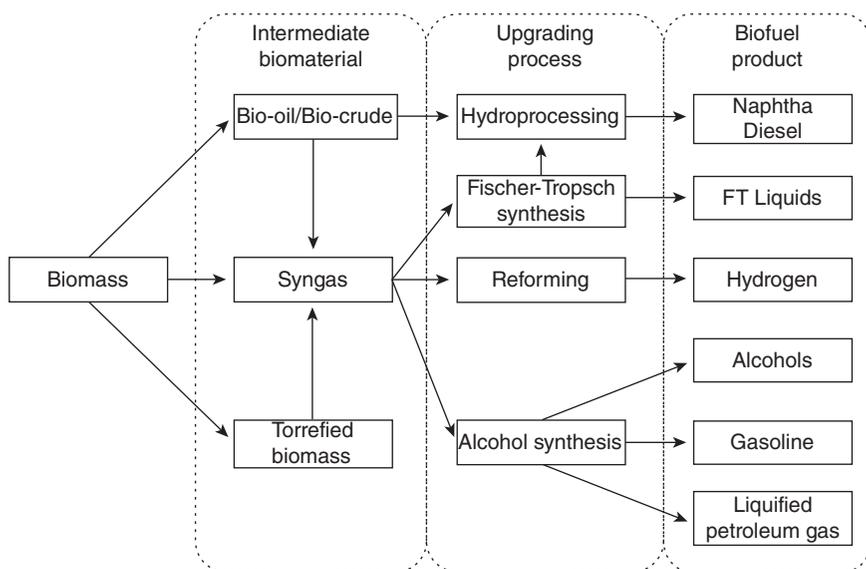
Recent biorefinery techno-economic papers have focused on advanced biorefineries based on the thermochemical and biochemical platforms. These papers assess the technical and economic viability of technologies ranging from the development phase up to demonstration stage. Some

assessments benefit from the data available for established commercial technologies employed in other industries. However, many of the advanced biorefinery technologies are first-of-a-kind facilities, which present a major engineering challenge. In this section, we discuss how insights provided by techno-economic analysis have contributed to our understanding of advanced thermochemical and biochemical biorefinery concepts.

2.2.1 Bioproducts from thermochemical biorefineries

Researchers have developed detailed TEAs for several biofuels including hydrogen, methanol, ethanol, mixed alcohols, Fischer–Tropsch liquids, and naphtha and diesel range blend stock fuels (Wright and Brown, 2007a). Biofuel synthesis pathways can be categorized by the feedstock intermediate, subsequent upgrading process, and type of biofuel output. Feedstock intermediates are classified here as the primary products from biomass torrefaction, pyrolysis, and gasification. Upgrading processes are associated with specific intermediate products, although torrefied biomass and bio-oil can be converted into syngas and upgraded through alternative pathways. An overview of the main thermochemical biomass-to-liquid fuel pathways is shown in Fig. 2.1.

The syngas pathway leads to several types of biofuel products depending on the upgrading process: alcohol synthesis can output mostly methanol,



2.1 Thermochemical biomass conversion pathway intermediates, upgrading processes, and final products.

ethanol, or mixed alcohols; methanol from alcohol synthesis can be further upgraded to gasoline and liquefied petroleum gas via the methanol-to-gasoline (MTG) process; steam reforming results in high hydrogen yields, and Fischer–Tropsch synthesis generates a mixture of hydrocarbons ranging from light gases to waxes ($C_1 \rightarrow C_{120}$). Fischer–Tropsch liquids can substitute for diesel, but they have slightly different properties than conventional diesel. Therefore, some studies include a hydroprocessing unit to increase the output of naphtha- and diesel-range biofuels.

Capital costs vary significantly between different biofuel synthesis routes and plant configurations. Table 2.1 shows capital costs for biomass conversion to hydrogen, methanol, mixed alcohols, and Fischer–Tropsch liquids via syngas production and conversion. These capital costs have been re-categorized from the original analyses according to major process steps or sections. In general, pretreatment includes feedstock drying and grinding; gasification consists of the gasifier and auxiliary equipment; oxygen separation refers to the air separation island; gas cleaning includes particulate, tar, and impurity removal; syngas conditioning refers to water gas shift or reforming processes required for synthesis; synthesis/production is the main step to produce the desired fuel based on given specifications; steam and power generation, and utilities/miscellaneous group all auxiliary units required for the overall operation of the facility.

The selection of processes shown in Table 2.1 includes high and low temperature gasifiers; oxygen and air blown gasification systems; and steam and power export configurations. High temperature gasifiers tend to be more expensive due to strict metallurgy and operating constraints, but they deliver a higher quality syngas, which reduces gas cleaning and conditioning costs. Air blown gasifiers do not require air separation equipment, which is expensive, but they dilute syngas with nitrogen, which increases the size of downstream equipment. Excess heat and fuel gas are typically converted into steam and/or power depending on the quantity and quality available.

Biofuel costs include feedstock and operating costs in addition to annualized capital costs. Feedstock costs typically contribute between a quarter and more than half of the final biofuel cost because of high biomass costs. By-products, mostly heat and power, can sometimes contribute significant revenue.

Table 2.2 shows the annualized costs for selected biofuels via the syngas pathway. These costs illustrate some of the differences in assumptions found in the literature. Although the biorefinery capacities are similar, the annualized capital, operation and management, and biomass costs vary widely. Annual capital expenditures, including depreciation and capital charges, depend on the estimates described in Table 2.1 and several financial assumptions. Operation and management costs are typically based on local labor rates and factors for equipment maintenance. The differences in

Table 2.1 Capital costs for biomass to fuel conversion via the syngas pathway

	Hydrogen (Hamelinck and Faaij, 2002)	Methanol (Hamelinck and Faaij, 2002)	Mixed alcohols (Phillips <i>et al.</i> , 2007)	Fischer– Tropsch liquids (Tijmensen <i>et al.</i> , 2002)	Gasoline (Phillips <i>et al.</i> , 2011)	Naphtha and diesel via FTL (Swanson <i>et al.</i> , 2010)
Cost basis (year)	2001	2001	2007	2001	2007	2007
Capacity (dry metric tonnes per day)	1920	1920	2000	1920	2000	2000
Capital costs (\$MM)						
Pretreatment	38.2	38.2	23.2	71.6	25.0	22.7
Gasification	73.0	30.4	12.9	61.4	14.6	67.8
Air separation	27.7	0	0	51.2	0	24.3
Syngas cleaning	12.4	38.1	14.5	61.4	44.3	33.5
Syngas conditioning	13.3	62.8	38.4	3.41	–	–
Synthesis/Production	53.3	41.3	27.8	20.5	21.6	49.4
Steam and power generation	64.8	13.9	16.8	61.4	23.1	45.6
Utilities/Miscellaneous	–	–	3.6	10.2	5.9	33.1
Total installed equipment cost	–	–	137	–	145	309
Total project investment	282	224	191	341	200	606

Table 2.2 Operating costs for biomass to fuel conversion via the syngas pathway

Operating costs (\$MM)	Hydrogen (Hamelinck and Faaij, 2002)	Methanol (Hamelinck and Faaij, 2002)	Mixed Alcohols (Phillips <i>et al.</i> , 2007)	Fischer– Tropsch liquids (Tijmensen <i>et al.</i> , 2002)	Gasoline (Phillips <i>et al.</i> , 2011)	Naphtha and diesel (Swanson <i>et al.</i> , 2010)
Capital	33.6	26.7	34.4	34.1	38.0	106.4
Operation and management	11.3	9.0	13.3	16.8	15.1	26.6
Biomass	24.7	24.9	27.0	34.2	39.1	51.3
By-product credit	–17.4	0.0	–12.8	0.0	0.0	–5.6
Total	52.1	60.6	61.9	50.8	92.2	178.7
Biofuel MFSP^a(\$/gal)	\$0.33	\$0.52	\$1.01	\$1.89^b	\$1.39	\$4.26
Biofuel MFSP (\$/gge^c)	\$1.26	\$1.05	\$1.54	\$1.77	\$1.39	\$4.26

^aMFSP: Minimum fuel selling price.

^bAssumes 34.4 MJ/L Fischer–Tropsch liquid energy density.

^cGGE: gallon of gasoline equivalent (32.3 MJ/L gasoline energy density).

biomass costs are due to the wide range of assumed feedstock prices (\$30–\$75 per metric ton). Finally, we should note that these cost assessments involve assumptions for process maturity and projections for technology improvement that significantly impact the final estimates.

There are fewer techno-economic analyses for alternatives to the syngas thermochemical pathway, such as bio-oil upgrading and hydroprocessing of lipids. This is due in part to the commercial maturity of these processes. There has been little commercial adoption in the biomass industry of alternative processes such as biomass pyrolysis to bio-oil and hydrothermal processing to bio-crude despite being under development since the 1970s. However, with rising petroleum costs, there is renewed interest in processes that replace petroleum products beyond transportation fuels.

The following processes adopt alternative routes to producing transportation fuels with valuable co-products. Biomass pyrolysis produces primarily bio-oil, which can be upgraded to fuels. Pyrolysis co-products include biochar – a soil amendment and potential carbon sequestration agent, and chemicals. Extraction and hydrolysis of bio-oil recovers sugars (pentose and hexose) that can subsequently be fermented to ethanol. Biorefineries could obtain high valued chemicals benzene, toluene, ethylene, and propylene among other hydrocarbons from bio-oil via integrated catalytic processing (ICP) using a modified HZSM-5 catalyst. Syngas fermentation could produce polyhydroxyalkonate (PHA), a biodegradable polymer, while yielding excess hydrogen. Table 2.3 shows capital and operating costs for these alternative biorefineries.

A small number of ventures have commercialized the hydroprocessing of lipids to renewable diesel and jet fuels. Commercial lipid hydroprocessing employs by-products from the food industry such as vegetable oils, waste oils, and fats. Algal biomass has the potential to become the main feedstock

Table 2.3 Capital and operating costs for alternative biorefineries producing ethanol, PHA, and aromatics and olefins

	Bio-oil fermentation (So and Brown, 1999)	Syngas fermentation (Choi <i>et al.</i> , 2010)	Bio-oil integrated catalytic processing (Brown <i>et al.</i> , 2012)
Product	Ethanol	PHA	Aromatics and olefins
Co-product	Sugars	Hydrogen	
Capacity (per year)	240 MM kg	6.5 MM kg	34.1 MM kg
Capital cost	\$69	\$103	\$100
Operating cost	\$39.2	\$18.2	\$74.5
Product cost	\$1.59/gal	\$2.80/kg	\$2.18/kg

for lipid hydroprocessing if its production costs are drastically reduced (Roesijadi *et al.*, 2010).

2.2.2 Bioproducts from biochemical biorefineries

The biochemical pathway in general, and fermentation to ethanol in particular, have been employed in the US and Brazil for several decades, and its economics have been thoroughly investigated. TEAs are available for the production of ethanol from sugarcane; the production of ethanol from corn (starch); and the production of ethanol from lignocellulose. More advanced pathways such as the production of ethanol from cyanobacteria and the production of hydrocarbons from sugar fermentation are also under investigation, although TEAs for these are not yet available.

The sugarcane pathway produces ethanol, electricity, and crystallized sucrose. Sugarcane is harvested and processed to separate the plant's lignocellulose (bagasse) from the cane juice (garapa). The bagasse is combusted to provide process heat and electricity, with the latter generated in sufficient quantities to be sold onto the neighboring electricity grid. The garapa is further processed into molasses and sucrose crystals. The molasses, which are a mixture of sucrose and minerals, are sterilized and fermented with brewer's yeast (*Saccharomyces cerevisiae*) to produce a beer containing 6–10 vol% ethanol. The beer is distilled to hydrous ethanol (containing 5 vol% water) via conventional distillation. Further dehydration can occur via employment of molecular sieves or other techniques to produce anhydrous ethanol (containing less than 0.3 vol% water).

The starch ethanol pathway most commonly employs corn (maize) as feedstock, although other starch crops such as wheat and cassava are also used. It is similar to the sugarcane ethanol pathway, although a saccharification step is required to depolymerize the starch into fermentable glucose monomers. The pathway employs either dry milling or wet milling, although TEAs of wet milling are very rare and it is not covered here as a result. In dry milling the corn kernels are ground, mixed with water, and cooked to gelatinize the starch content. Enzymes are added to depolymerize the starch first to oligosaccharides and then to the monosaccharide glucose (the process is also known as saccharification). The resulting fermentation broth also contains the lipid, fiber, and protein content of the kernel, which are removed and sold following fermentation as distillers' dried grains and solubles (DDGS), a valuable livestock feed. Fermentation employs *Saccharomyces cerevisiae* and is followed by distillation and dehydration to anhydrous ethanol.

Table 2.4 reviews the capital costs for a Brazilian sugarcane ethanol biorefinery and a US corn ethanol dry mill biorefinery. Equipment components are not identical due to feedstock-specific differences between

Table 2.4 Capital costs for first generation ethanol biorefineries

	Sugarcane ethanol (Efe <i>et al.</i> , 2005)	Corn ethanol dry milling (Kwiatkowski <i>et al.</i> , 2006)
Cost basis (year)	2005	2005
Capacity (million gallons per year)	50	40
	Capital costs (\$MM)	
Milling	3.8	3.4
Clarification	2.6	–
Evaporation	7.6	–
Crystallization and drying	4.0	–
Saccharification	–	5.3
Fermentation	4.2	10.5
Distillation	4.0	8.0
Coproduct processing	19.7	19.5
Total installed equipment cost	45.9	46.7
Total project investment	101.9	103.7^a

^aAdjusted to account for indirect costs not included in original assessment.

Table 2.5 Operating costs for first generation ethanol biorefineries

Operating costs (\$MM)	Sugarcane ethanol (Efe <i>et al.</i> , 2005)	Corn ethanol dry milling (Kwiatkowski <i>et al.</i> , 2006)
Capital depreciation	10.2	10.4*
Operation and management	12.2	13.3
Biomass	64.2	35.1
By-product credit	–77.4	–11.7
Total	9.2	47.1
Biofuel price (\$/gal)	\$0.82	\$1.17 ^a
Biofuel price (\$/gge)	\$1.23	\$1.76 ^a

^aAdjusted to account for indirect costs not included in original assessment.

the pathways: a sugarcane ethanol biorefinery requires equipment to process the garapa into molasses and sucrose crystals, whereas a corn ethanol biorefinery requires equipment to convert starch into dextrose via enzymatic hydrolysis. The corn ethanol facility is more expensive on an equal capacity basis as a result of the saccharification step and increased fermentation and distillation steps.

Table 2.5 reviews the operating costs for sugarcane to ethanol and starch ethanol dry milling biorefineries. While sugarcane ethanol biorefineries pay nearly twice as much in annualized costs for feedstock than do corn ethanol

biorefineries of comparable ethanol output, they also derive significantly more revenue from by-product credits in the form of electricity and crystallized sucrose sales. These by-product credits cause the total annualized operating costs to be lower for a sugarcane ethanol biorefinery than a corn ethanol biorefinery despite the former's higher feedstock costs, resulting in a lower biofuel production cost for sugarcane ethanol than corn ethanol.

Lignocellulosic biomass can also be converted into ethanol via fermentation, although the recalcitrance of cellulose (a linear-chain polysaccharide) and the antimicrobial properties of lignin make it a significantly more challenging and expensive pathway than first generation ethanol pathways. The biomass is first milled to increase the surface area of the lignocellulosic material and increase hydrolysis efficiency. A pretreatment step is also commonly employed to maximize hydrolysis efficiency and dilute acid, steam explosion, and ammonia fiber explosion are considered to be the most feasible (Kazi *et al.*, 2010). The choice of pretreatment step affects both biorefinery operating costs and ethanol yields.

Pretreatment is followed by hydrolysis. One of three hydrolysis steps is employed to convert cellulose and any hemicellulose remaining following pretreatment into fermentable monosaccharides: concentrated acid, dilute acid, or enzymatic. Concentrated acid hydrolysis is employed in multiple cellulosic ethanol biorefineries but has not been the subject of TEAs and therefore is not covered here. Dilute acid hydrolysis is faster than enzymatic hydrolysis but can generate lower yields of monosaccharides. Recent research has also called into question existing cost estimates of the enzymes employed by enzymatic hydrolysis (Klein-Marcuschamer *et al.*, 2012), suggesting that dilute acid hydrolysis could incur lower operating costs of the two processes (Kazi *et al.*, 2010).

Table 2.6 presents capital cost estimates from three different TEAs for lignocellulosic biorefineries employing a dilute acid pretreatment and enzymatic hydrolysis. There is some variation in the equipment costs used to calculate total project investment, although Humbird *et al.* (2011) and Kazi *et al.* (2010) are very close when adjusted for capacity. The estimate from Piccolo and Bezzo (2007) is comparatively low, although this can be attributed to low estimates for distillation and recovery equipment and exclusion of the feedstock handling area, demonstrating the importance of the assumptions used in a TEA. Total project investment from these studies is 200–300% higher than for first generation biorefineries due to the necessity of including expensive pretreatment and hydrolysis equipment.

Table 2.7 presents annual operating cost estimates from three different TEAs for lignocellulosic biorefineries employing a dilute acid pretreatment and enzymatic hydrolysis. Humbird *et al.* (2011) is different from the other two assessments in that it models on-site enzyme production for hydrolysis; both Kazi *et al.* (2010) and Piccolo and Bezzo (2009) model enzyme purchase

Table 2.6 Capital costs for lignocellulosic ethanol biorefineries employing dilute acid pretreatment and enzymatic hydrolysis

	Humbird <i>et al.</i> (2011) (Humbird and Aden, 2009)	Kazi <i>et al.</i> (2010)	Piccolo and Bezzo (2007)
Cost basis (year)	2007	2007	2007
Capacity (million gallons per year)	61	53	51
Capital costs (\$MM)			
Feedstock handling	24.2	10.9	–
Pretreatment	29.9	36.2	31.5
Conditioning	3.0	–	–
Hydrolysis and fermentation	31.2	21.8	12.9
Enzyme production	18.3	–	–
Distillation and recovery	22.3	26.1	4.3
Wastewater	49.4	3.5	10.4
Storage	5.0	3.2	–
Boiler	66.0	56.1	44.5
Utilities	6.9	6.3	11.2
Other	18.3	–	–
Total installed equipment cost	274.6	164.1	114.7
Total project investment	422.5	375.9	270.8

Table 2.7 Operating costs for lignocellulosic ethanol biorefineries employing dilute acid pretreatment and enzymatic hydrolysis

Operating costs (\$MM)	Humbird <i>et al.</i> (2011) (Humbird and Aden, 2009)	Kazi <i>et al.</i> (2010)	Piccolo and Bezzo (2007)
Capital depreciation	60.4	16.3	37.8
Operation and management	24.2	71.8	89.7
Biomass	45.2	57.9	47.6
By-product credit	–6.6	–11.7	–2.1
Total	123.2	134.3	173.0
Biofuel price (\$/gal)	\$2.15	\$3.40	\$2.87
Biofuel price (\$/gge)	\$3.23	\$5.10	\$4.29

from external sources. On-site enzyme production generates higher capital costs (as evidenced by greater capital depreciation) and lower operation and management costs.

2.2.3 Power generation at biorefineries

Biorefineries can choose to generate electricity from biomass or byproducts into electricity. Although biomass electricity is typically more expensive than fossil fuel power, there are two scenarios where biomass power is an obvious choice: remote or stranded biomass supply, and production of excess byproducts.

There are large quantities of biomass in remote or stranded locations that are classified as wastes. A significant amount of this waste decomposes without yielding economic value. This loss occurs, in part, because waste biomass is difficult to gather reliably in sufficient quantities, and waste is a heterogeneous material which makes conversion difficult. Small-scale power generation is one way to capitalize on potentially low-cost feedstock.

Biomass power generation can be accomplished in several ways: biomass combustion can provide steam to drive a steam turbine; biomass gasification yields syngas that could be fed into a gas turbine; biomass pyrolysis or torrefaction yield intermediate materials that can be combusted or gasified to produce power. Representative costs for these three scenarios are given in Table 2.8.

The low capital costs (\$600/kW) for biomass combustion to power are indicative of the technology's simplicity (Dornburg and Faaij, 2001; Jenkins *et al.*, 2011). However, biomass combustion is less efficient than the alternatives even at large scale. Biomass gasification for power generation requires additional capital investment for the more expensive gas turbines and auxiliary equipment to ensure that gas conditions meet strict particulate matter requirements. The higher costs are compensated by higher efficiencies and ability to scale resulting in lower operating costs. The gasification scenario allows for the use of an integrated gas combined-cycle (IGCC) design with both steam and gas turbines to further improve the process

Table 2.8 Capital and operating costs for biomass power generation

Technology	Capital cost (kW ⁻¹ capacity)	Operating cost (kWh ⁻¹)
Combustion to power (Dornburg and Faaij, 2001)	\$600	\$0.075
Gasification to power	\$1600	\$0.05
Pyrolysis to power (Bridgwater <i>et al.</i> , 2002)	\$2400	\$0.08

efficiency. Finally, the power industry has shown interest in pyrolysis and torrefaction products as a means to overcome some of the challenges faced by biomass, e.g. storage, heating value, feeding. Pyrolysis and torrefaction processes yield products that can be stored with less degradation and a lower footprint, that have a higher heating value, and are easier to feed into existing equipment than raw biomass. These benefits come at a cost. Capital costs are expected to be much higher than conventional alternatives (\$2400/kW) with higher operating costs as well (\$0.08/kWh) (Bridgwater *et al.*, 2002).

2.3 Trade of biomass and subsidies

2.3.1 Biomass cost estimates by feedstock type

Lignocellulosic biomass feedstocks employed by biorefineries can broadly be divided into two categories: dedicated energy crops and residues. Dedicated energy crops are crops grown specifically for use as biomass feedstocks in biorefineries. These are divided into two further categories: herbaceous energy crops and short-rotation woody crops. Herbaceous energy crops contain little to no woody material and are exemplified by grasses. Common examples include switchgrass, *Miscanthus giganteus*, and energy cane. Short-rotation woody crops are softwoods and hardwoods with short harvest rotations. Common examples include hybrid poplar and *eucalyptus*. Short-rotation woody crops have longer harvest rotations than most herbaceous crops but compensate for this by also producing higher yields by biomass weight.

Biomass residues are waste products from either urban or rural areas. Residues from urban areas include both municipal solid waste (MSW) and processing residues from factories and manufacturing centers utilizing biomass as an input. Residues from urban areas are characterized by high concentration and low costs due to the avoidance of tipping fees otherwise paid to waste haulers. The disadvantages to using urban residues as biorefinery feedstocks are their heterogeneous nature (for example, MSW frequently contains plastics, metals, and glass capable of damaging a biorefinery) and high values for nearby land, thereby increasing biorefinery costs in the form of either capital or transportation costs. Biomass residues from rural areas most commonly take the form of agricultural residues left on the field after a crop harvest, such as corn stover. These are spread out over a large area and require specialized collection equipment, resulting in higher costs as biorefinery feedstocks than urban residues. Agricultural residues have the advantages of being homogeneous and located near inexpensive land, allowing biorefineries employing them as feedstock to minimize both capital and transportation costs.

Two methods are employed for estimating biorefinery feedstock costs. The first is the use of field trials that account for detailed costs of feedstock production, collection, transportation, and mitigation of negative environmental effects (e.g., nutrient replacement necessitated by the removal of corn stover). Several studies employing field studies have calculated the cost of agricultural residues to be lower than the cost of dedicated energy crops; the delivered cost of stover is calculated to be in the range of \$47/MT to \$75/MT (Brechbill *et al.*, 2011; Perlack and Turhollow, 2003; Petrolia, 2008) while that of switchgrass is calculated to be in the range of \$80/MT to \$96/MT (Brechbill *et al.*, 2011). The disparity between the costs of agricultural residues and dedicated energy crops is due to the fact that residues do not require an accounting of production costs and opportunity costs, as they are produced during the normal course of crop production and just need to be collected and transported to the biorefinery. Dedicated energy crops must account for these costs in addition to production and opportunity costs.

The second method employed for estimating biorefinery feedstock costs is the use of economic models based on a combination of field trials, supply chain data, and macroeconomic prices. Two recent examples have been developed by researchers at North Carolina State University (Gonzalez *et al.*, 2011) and the National Research Council (Committee on Economic and Environmental Impacts of Increasing Biofuels Production, 2011). In both cases the costs estimated by the economic models have been greater than those from field trials, with the delivered cost of switchgrass ranging from \$94/MT to \$108/MT and stover ranging from \$96/MT to \$101/MT.

The higher cost estimates from the economic model methodology relative to the field trial methodology can be attributed to the highly specific and localized nature of the latter. Field trials are commonly performed at the farm- or county-scale, which are then sometimes extrapolated to the state-scale. While this entails a high degree of accuracy on smaller scales, these results are not suitable for analyses at the regional or national scale. Economic models produce results at the regional or national scale and, while they do not have the levels of detail and accuracy found in field trials, they are more suitable for large-scale analyses.

2.3.2 Federal subsidy programs

The United States has employed a number of biofuel subsidy and tariff programs since the 1970s that have influenced the economic feasibility of biorefineries. The majority of these programs expired at the end of 2011 (Pear, 2012) and the US government has switched the focus of biofuels policy from protectionist programs to a low-carbon mandate in the form of the Renewable Fuel Standard. Whereas past biofuels programs have focused

primarily on first generation biofuels and ethanol pathways, the current mandate is broader in scope and includes biofuel pathways ranging from ethanol to butanol to biobased gasoline and diesel (so-called drop-in biofuels).

Up until their expiration at the end of 2011, the US maintained a redeemable tax credit (i.e., a credit first applied against a taxpayer's tax burden with any excess being received as a direct payment) worth \$0.45 for every gallon (\$0.12/liter) of pure ethanol blended with gasoline for use as transportation fuel in the form of the volumetric ethanol excise tax credit (VEETC). A concurrent tariff on ethanol imports was also employed to prevent foreign ethanol producers (particularly Brazilian, as sugarcane ethanol has historically been cheaper to produce than corn ethanol) from utilizing the subsidy. Ethanol importers were required to pay a 2.5% *ad valorem* tariff plus a fixed \$0.54/gal tariff on all imported ethanol. This had the effect of making Brazilian sugarcane ethanol more expensive in the US than US corn ethanol (see Table 2.5) despite the former's smaller production costs. A number of smaller subsidy programs affected other biofuel pathways. Biodiesel producers received a \$1 non-refundable tax credit (i.e., a credit applied only to a taxpayer's tax burden) for every gallon (\$0.26/liter) blended with diesel or sold as fuel. Cellulosic ethanol producers received (and still receive) a \$1.01 non-refundable tax credit for every gallon (\$0.27/liter) of cellulosic ethanol blended with gasoline or sold as fuel in the form of the cellulosic biofuel producer tax credit (CBPTC). Non-refundable tax credits were also available for small ethanol producers and liquefied gas producers.

Popular concerns that corn ethanol production was causing starvation in the developing world (Runge and Senauer, 2007) and deforestation in the Amazon (Searchinger *et al.*, 2008) combined with a shift toward government austerity in the US to undermine political support for first generation biofuel protectionism. With the exception of the CBPTC, all of the aforementioned subsidy and tariff programs were allowed to expire by Congress at the end of 2011, leaving the Renewable Fuel Standard as the primary driver of US biofuel policy. The first iteration of the Renewable Fuel Standard (RFS1) was created by the Energy Policy Act of 2005 to serve as a simple biofuel mandate. Rapid growth in US corn ethanol production left it obsolete soon after its creation and the Energy Independence and Security Act of 2007 replaced it with a greatly expanded (both in scope and volume) Renewable Fuel Standard (RFS2). The RFS2 combines an increased biofuel mandate (36 million gallons (136 million liters) per year by 2020) with a low-carbon fuel standard (LCFS). Four separate yet nested biofuel categories exist whereas the RFS1 had only one: (1) total renewable fuels, (2) advanced biofuels, (3) biomass-based diesel, and (4) cellulosic biofuels. Each category has a particular volumetric mandate that changes

over time; total renewable fuels comprise the majority of the mandate but are permanently capped in 2015, and by 2022 the cellulosic biofuel category becomes responsible for a plurality of the mandate.

The definitions of each RFS2 category encompass both biofuel type and feedstock source (Energy Independence and Security Act, 2007). To qualify for the total renewable fuels category, a biofuel must be sourced from renewable biomass (i.e., biomass meeting land-use restrictions) and achieve a 20% lifecycle greenhouse gas emission (GHG) threshold relative to gasoline. Advanced biofuels must achieve a 50% GHG reduction and cannot include corn ethanol (regardless of its lifecycle GHG analysis). Biomass-based diesel must also achieve a 50% GHG reduction and includes both biodiesel produced via transesterification and renewable diesel. Finally, cellulosic biofuels must achieve a 60% GHG reduction versus gasoline and be sourced from lignocellulosic feedstocks. Emissions from indirect land-use changes (ILUC) must be accounted for when determining whether a biofuel achieves a category's GHG reduction threshold.

The RFS2 impacts the economic feasibility of biorefineries by attaching a renewable identification number (RIN) to every gallon of biofuel blended with or sold as transportation fuel in the US. The RFS2 requires blenders to own a certain number of RINs proportionate to their market share at the end of each year to demonstrate compliance with the mandate. A blender that has met its share of the mandate can sell any excess RINs to a blender that has not, or can bank them for future use. RIN values increase when the supply of biofuels within an RFS2 category exceeds demand and can serve as an important source of income for biofuels producers, as RIN values for the biomass-based diesel category reached \$1.60/gal in August 2011 (McPhail *et al.*, 2011). When demand exceeds supply (i.e., when the mandate has not been met), the core value of an RIN is the difference between the biofuel's production cost and the market price of gasoline or diesel (RIN values do not drop below 0 when this market price exceeds the biofuel's production cost). RINs are allowed to be publicly traded, however, so speculator activity can also affect RIN value.

The effect of the RINs is to ensure that biofuel producers receive the minimum value necessary to cover costs of production. When gasoline and diesel prices are greater than biofuel production costs, then the core RIN value is 0, as biofuel producers do not need additional incentive to produce up to the mandated volume. When gasoline and diesel prices are less than biofuel production costs, then the core RIN value increases to the level necessary to incentivize sufficient production to meet the mandate. As an example, assume that the three lignocellulosic ethanol TEA results presented in Table 2.7 are three different biorefineries and the cellulosic ethanol produced by each qualifies for the cellulosic biofuels category of the RFS2. Initial production will fall short of the mandated volume (the

EPA has waived the cellulosic biofuels mandate in recent years due to a complete lack of production) and, assuming a pre-tax gasoline price of \$3/gal, the RIN value will be sufficiently high to incentivize production at all three biorefineries, or \$2.10/gge (the difference between the highest biofuel production cost, \$5.10/gge, and the pre-tax gasoline price). The biorefinery capable of achieving the lowest production cost will attain the greatest profit but all three will be profitable. This will change as total cellulosic biofuel production exceeds the mandated volume, however. Assuming the first two biorefineries produce enough to satisfy the mandate and the pre-tax gasoline price remains \$3/gal, then the RIN value will decline to the difference between the pre-tax gasoline price and the second highest biofuel production cost (\$4.29/gge), or \$1.29/gge. In this way, the RFS2 ensures that biofuel producers remain economically feasible when gasoline and diesel prices are low while eliminating the prospect of government-subsidized windfall profits when gasoline and diesel prices are high.

2.3.3 State subsidy programs

A number of states have implemented subsidy programs to encourage local biofuel production. These programs range from renewable portfolio standards (RPS) to state-wide blending requirements to low- and zero-interest loans for the construction of biorefineries. Blending requirements and RPSs both indirectly affect the economic feasibility of biorefineries by creating demand for their products. Blending requirements mandate the blending of certain volumes of ethanol with gasoline and biodiesel with diesel fuel (usually 5 vol%, although this varies by state) for fuel sold within the state. RPSs mandate that a certain amount of electricity sold within the state come from renewable sources such as a cellulosic ethanol biorefinery.

States have also attempted to attract biorefinery construction by offering low- or zero-interest loans to biofuel companies for their construction within the state. For example, drop-in biofuel company KiOR has received a zero-interest \$75 million loan from the state of Mississippi for the construction of a commercial-scale catalytic pyrolysis and upgrading facility within the state (Dolan, 2011). Such loans improve the economic feasibility of recipient biorefineries by eliminating interest payments on initial capital costs. Unlike blending requirements and RPSs, favorable loans are generally directed at individual companies rather than made available for all qualifying producers.

2.3.4 European Union subsidy programs

The European Union (EU) has implemented a number of programs incentivizing the production of biorenewable energy, both on a Eurozone

scale and a national scale by its member nations. The various programs are broadly split into the categories of biorenewable electricity and biofuels. The EU's 2009 Renewables Directive (Anon., 2009a) creates two separate binding targets for member nations. First, EU members must derive 10% of their transport energy from renewable sources, including biomass, by 2020. Second, they must also derive 20% of all of their energy from renewable sources, including biomass, by 2020. Member nations are given the flexibility to determine how best to meet these targets. Additionally, the EU has established economic mechanisms to compensate participating facilities within member nations that contribute to reducing greenhouse gas emissions (GHG).

The EU has implemented an Emission Trading Scheme (ETS) to combat anthropogenic climate change resulting from GHG via a cap-and-trade mechanism. Installations located within a member nation that meet a net heat threshold are covered by the ETS. Each member nation receives annually a limited number of GHG emission allowances that are distributed to covered installations, which must in turn purchase additional allowances for any emissions that exceed this allocation.

The ETS affects biorefineries both directly and indirectly. It directly affects biorefineries by allowing them to receive offset credits in the form of emission reduction units (ERU). ERUs are awarded in exchange for activity that results in the avoidance of GHG emissions. Example projects include the production of biogas from landfills for use as fuel, the utilization of waste sawdust as electricity or biofuel feedstock, and the use of sunflower and canola oils as biodiesel fuel feedstocks (Fenhann, 2012). Each ERU represents 1 metric ton (MT) of avoided GHG emissions and can be traded with other parties. In this way, ERUs can directly contribute to the economic feasibility of a qualifying biorefinery by representing an additional value-added product.

The ETS indirectly affects biorefineries by artificially increasing the cost of fossil fuel products relative to renewable fuel products in proportion to their respective carbon footprints. Power plant operators must purchase sufficient carbon allowances to cover the plant's GHG emissions, the size of which is determined by the feedstock utilized. This increases the value of electricity derived from biorenewables by lowering its cost relative to electricity derived from fossil fuels and thereby increasing demand for it. A similar situation exists for qualifying transportation biofuels. For example, the EU's decision in 2012 to include airlines operating in Europe within the ETS (Torello *et al.*, 2012) enhanced the value of aviation biofuel, as one method by which covered airlines can avoid GHG emissions (and the need to purchase additional allowances) is by combusting biofuel instead of conventional fossil fuel-based aviation fuel during flights.

2.3.5 EU member nation subsidy programs

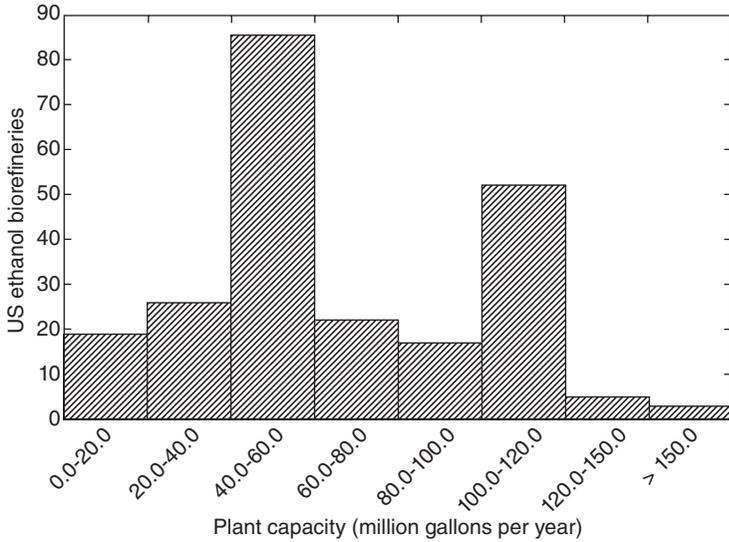
A number of EU member nations have implemented their own programs incentivizing biorenewables as part of the binding targets imposed by the 2009 Renewables Directive. A wide variety of program types are employed, ranging from feed-in tariffs to mandates to tax incentives. The United Kingdom's (UK) Renewables Obligation establishes a mandate of 20% renewable electricity generation in the country by 2020 (Swinbank, 2009). The UK's Renewable Transport Fuels Obligation also establishes a mandate for 5 vol% of UK transport fuel consumption to be derived from renewable sources by 2013. Germany initially took a different approach by levying a tax on fossil fuels that was not applied to biofuels before switching to a biofuels mandate in 2007 (Deurwaarder, 2007). The large majority of EU member nations encourage the production of biofuels via tax incentives, blending requirements, or a combination of the two (Pelkmans *et al.*, 2008).

2.4 Market establishment: national/regional facilities

Biomass supply chains span from local collection efforts to international networks. National and regional biorefineries can thus be classified by the extent of their supply networks and product distribution. Most biorefineries are small-scale, regional facilities that collect feedstock from within a state or region. On the other hand, large-scale, national biorefineries would transport biomass across state borders to meet demand.

A majority of US ethanol biorefineries generate less than 80 million gallons (303 million liters) per year as shown in Fig. 2.2 (Anon., 2009b). At this capacity, biorefineries can collect enough corn from surrounding counties. In Iowa, for example, corn ethanol biorefineries receive their feedstock from an average distance of 28 miles (45 kilometers) (Anon., 2008). Nearly half of corn suppliers use tractor-pulled wagons while others employ straight trucks, fifth wheels or semi-trucks. Although short transport distances characterize corn supply, corn ethanol travels much farther. Corn biorefineries employ rail, trucks, and barges to ship ethanol to demand centers both within the county and across multiple state borders.

National, and international, biorefineries are defined here as facilities that receive feedstock by multiple transportation modes and from regions hundreds of miles from the facility. The large supply networks required to feed these types of biorefineries pose key economic challenges that differ from those faced by the fossil fuel industry. The biomass industry is still trying to understand the nature of these challenges and develop ways of addressing them.



2.2 US ethanol biorefinery capacities per year.

2.4.1 Biomass logistics and transport infrastructure

Biomass is a diffuse resource that requires significant investment to collect and transport to a biorefinery. There are numerous studies on biomass logistics. Recent developments in geographic information systems (GIS) and operations research (OR) allow for increasing level of detail in logistic studies. In general, logistic studies attempt to estimate the costs for biomass collection, storage, and transportation.

Researchers at Iowa State developed estimates for feedstock suppliers' willingness to accept (WTA) selling price based on the following equation (Miranowski and Rosburg, 2010):

$$WTA = \left\{ \frac{C_{ES} + C_{Opp}}{Y_B} + C_{HM} + SF + C_{NR} + C_S + DFC + DVC * D \right\} - G \quad [2.1]$$

where C_{ES} stands for establishment and seeding costs, C_{Opp} represents land and biomass opportunity costs, Y_B is the biomass yield, C_{HM} are harvest and crop maintenance costs, SF are stumpage fees, C_{NR} are nutrient replacement costs, C_S is storage, DFC and DVC are the fixed and variable transportation costs, respectively, D is the distance to the biorefinery, and G are governmental incentives.

Biomass production incurs sunk costs in the form of establishment, opportunity, and nutrient replacement costs. Establishment costs can be ignored for biomass residue, but they are important for dedicated energy

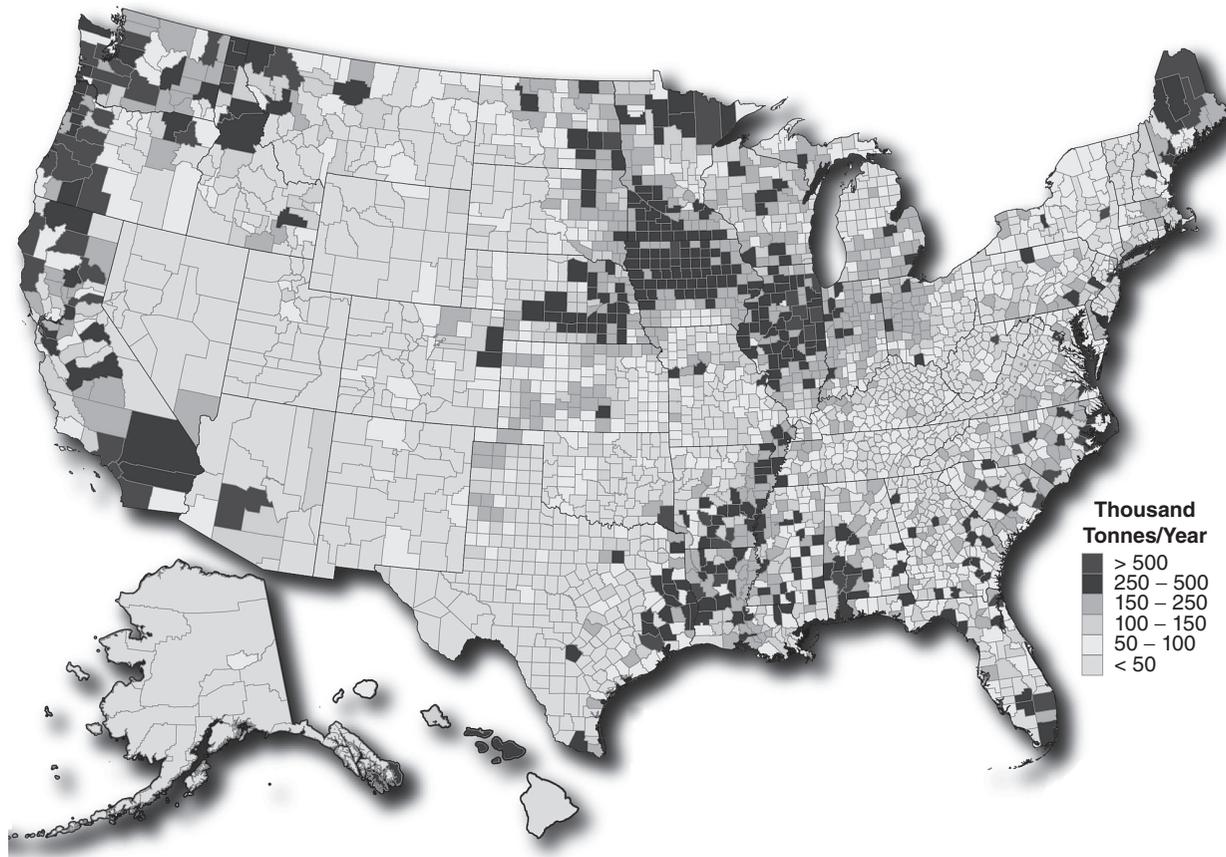
crops. Biomass land and opportunity account for the loss revenue from growing alternative crops and land rental value. The removal of significant quantities of waste material would require nutrient addition in order to maintain soil quality.

Biomass collection varies between different types of feedstock. The corn, and sugarcane, industry has developed specialized machinery that collects grain at low cost: harvesting costs account for less than 15% of corn costs (Duffy, 2012). Collection costs for other types of feedstock have higher contributions to the overall cost. Harvesting cost estimates for corn stover, switchgrass, and *miscanthus* range between \$14 and \$84 per dry ton (\$15 and \$93 per dry ton) (Committee on Economic and Environmental Impacts of Increasing Biofuels Production, 2011), which could represent between 10 and over 80% of the delivered feedstock cost.

Cost estimates for biomass transport vary widely. They vary due to a lack of consistent data and because of the different methods employed. Transportation costs are typically reported as a total delivered cost or with fixed and variable components. DVC costs range between \$0.09 and \$0.60 per dry ton per mile (\$0.06 and \$0.41 per dry ton per km). DFC costs range between \$4.80 and \$9.80 per dry ton (\$5.30 and \$10.8 per dry ton).

Location is a major factor in the overall costs of delivering biomass to a facility. Land productivity, transportation networks, and storage facilities are a few of the parameters that vary significantly across various locations. GIS software provides display and analytical capabilities to investigate biomass supply chains. The US government provides a wealth of data in the form of GIS maps and dataset through their centralized portal www.data.gov. An example is shown in Fig. 2.3, which illustrates the distribution of total biomass resources in the US. There are high concentrations of biomass in the Midwest (stover), Pacific, Atlantic, and Gulf Coast (wood) regions, and around large metropolitan areas (MSW). This study estimates the biomass resources currently available in the United States by country. It includes the following feedstock categories: crop residues (5 year average; 2003–2007), forest and primary mill residues (2007), secondary mill and urban wood waste (2002), methane emissions from landfills (2008), domestic wastewater treatment (2007), and animal manure (2002). For more information on the data development, please refer to <http://www.nrel.gov/docs/fy06osti/39181.pdf>. Although, the document contains the methodology for the development of an older assessment, the information is applicable to this assessment as well. The difference is only in the data's time period.

The operations research field has developed mathematical formulas that evaluate biomass logistics within a geographical context. These formulas can estimate costs for a given region (city, municipality, county, state, agricultural district, nation, international) with improved relevance. Biomass supply formulations typically involve an objective function, several variables



2.3 US total biomass (grain, waste, wood) county-level supply (Milbrandt 2005, produced by the National Renewable Energy Laboratory for the US Department of Energy).

or parameters, and multiple constraints. For example, we could reduce biorefinery feedstock costs by minimizing suppliers' WTA price:

$$\min \sum_{i=0, j=0}^{n, m} \left\{ \frac{C_{ES, i} + C_{Opp, i}}{Y_{B, i}} + C_{HM, i} + SF_i + C_{NR, i} + C_{S, i} + DFC + DVC * D_{ij} \right\} * F_{ij} - G * F_{ij} \quad [2.2]$$

subject to

$$\sum_{i, j=0}^m F_{ij} \leq Biomass_i \quad \forall i \in n$$

$$\sum_{i=0, j}^n F_{ij} \geq Demand_j \quad \forall j \in m$$

variable F_{ij}

\forall : for all; \in : in

where i and j are subscripts representing biomass supply and biorefinery locations respectively, F is the amount of biomass shipped from i to j , n is the set of biomass supply counties, and m is the set of biorefinery locations. The *Biomass* constraint ensures that no more than the available amount of biomass gets shipped from a supply count, and the *Demand* constraint requires that the biorefinery receive enough biomass to satisfy their full capacity. This simple formulation can be expanded to include dynamic or temporal considerations, multi-level supply chains, and social and environmental parameters.

2.4.2 Scale-up of biorefinery operations

Biorefinery scale-up is a common approach to reducing costs by capital intensification. This approach has been proven in the fossil fuel industry where the average US coal plant generates over 227 gigawatts (in comparison, the energy production rate of a 100 million gallon (379 million liter) per year ethanol plant is equivalent to about 280 megawatts). Although biorefineries can benefit from economies of scale, they also suffer from diseconomies of scale that limits their ability to increase capacity (Wright and Brown, 2007b). Here we discuss the impact of scale on biorefinery costs and strategies to mitigate diseconomies of scale.

Product costs consist of three major categories: capital, operating, and feedstock costs. Capital costs include equipment depreciation, taxes, and the return on investment required to recoup the initial capital with a desired profit. Operating costs are expenses required to operate the facility such as

labor and maintenance. Finally, feedstock costs are spent to acquire requisite raw materials. These costs are difficult to estimate, which has led to the development of sophisticated tools that depend on prior knowledge to determine costs for novel processes.

Product costs are a function of a plant's capacity. The relationship between a plant's capacity and the various cost components can be approximated with power law equations (Wright and Brown, 2007b):

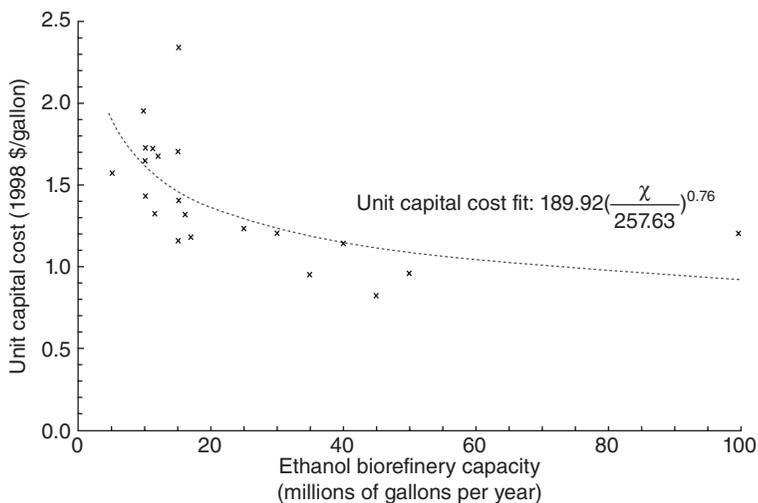
$$Fuel\ Cost_M = C_0 * \left(\frac{Capacity_M}{Capacity_0} \right)^n + O_0 * \left(\frac{Capacity_M}{Capacity_0} \right)^m + F_0 * \left(\frac{Capacity_M}{Capacity_0} \right)^p \quad [2.3]$$

where C , O , and F stand for capital, operating, and feedstock costs. Variables with subscript 0 correspond to known costs and capacities for a baseline facility. The scale factors n , m , and p relate to the scaling behavior of each cost component. Scale factor values vary between technologies, but there are commonly accepted values employed in industry for major facility categories. In the thermochemical industry, n is commonly assumed as 0.63 or 0.7, m is approximately linear (between 0.9 and 1), and p can be either smaller or greater than 1. In general, scale factors that are less than unity represent product costs that decrease with plant capacity. For example, a 0.7 scale factor suggests that every 1% increase in capacity incurs a smaller 0.7% increase in capital costs. Biorefineries are unique in the fuel industry for having large p scale factors (in the order of 1.5), meaning that feedstock costs increase with plant capacity. Figure 2.4 shows unit capital costs of corn ethanol biorefineries versus plant capacity.

Economies of scale are strong incentive to build large biorefineries. However, beyond an optimal capacity, feedstock transportation costs increase at a faster rate than reductions in capital costs. Engineers are evaluating distributed processing strategies to alleviate transport costs.

Distributed processing is the notion that small-scale facilities pretreat biomass prior to shipping to a large, upgrading facility. This concept yields several economic benefits: reduced storage space requirement, slower biomass degradation rates, and improved energy densities. Pretreatment intensity varies from simple drying and grinding to torrefaction or even pyrolysis.

Biomass drying and grinding removes moisture, which can otherwise increase biomass degradation rates by encouraging microbial activity. Grinding increases the feedstock bulk density and allows for pelletization, which is the mechanical compression of loose material into dense pellets. Torrefaction increases the energy density by further lowering the moisture content, releasing low energy value compounds, and slightly modifying biomass structure. Torrefied biomass is hydrophobic, which makes it



2.4 US corn ethanol plant unit capital costs vs. capacity ($n \approx 0.84$) (Gallagher *et al.*, 2005).

ideal for long-term storage. Torrefaction allows for efficient biomass pulverization, which increases the energy density. Finally, biomass pyrolysis, or liquefaction techniques, convert biomass into a liquid form with high material density. Pyrolysis oil, combined with biomass char materials, is an energy dense material that could be shipped at low cost, but corrosion remains a challenge.

Distributed processing in specialized, small-scale facilities or depots will play an important role in a large-scale biorefinery industry (Wright and Brown, 2007b). Without pretreatment, biomass transportation will be expensive and increase the number of trucks delivering material to central facilities. Unfortunately, distributed processing faces the classical ‘chicken or egg’ problem: without large-scale facilities there is a limited market for pretreated biomass feedstock, and without distributed processing facilities may find it difficult to achieve large-scale capacities. Pretreatment technologies may initially feed into the existing fossil fuel infrastructure by delivering torrefied biomass to coal plants or bio-oils to oil refineries. However, some technical and economic hurdles for this alternative remain unsolved.

2.5 Conclusion and future trends

TEAs are evolving to address challenges faced by novel biorefinery technologies: lack of processing data, concern for environmental impacts,

need for risk and uncertainty quantification, and desire for process optimization. This evolution has consisted of extending traditional TEA techniques and/or combining with advances in related disciplines.

2.5.1 Public support of pilot and demonstration biorefineries

Lack of industrial data to support TEA has prompted government initiatives to sponsor the construction of pilot- and demonstration-scale biorefineries such as the National Advanced Biofuels Consortium (NABC). These initiatives help gather process data that guides the direction of future public funding in biofuels research and development.

Industry has yet to meet the RFS2 mandates for advanced cellulosic biofuel production. In fact, the Environmental Protection Agency (EPA) retroactively reduced the 2011 mandate from 250 million gallons (946 million liters) to 6.5 million gallons (25 million liters). The United States Department of Agriculture attributes the lack of advanced biofuel supply to several factors including the high cost of first-of-a-kind biorefineries (Coyle, 2010). Lack of financial investment in these technologies is exacerbated by the lack of industrial data to support them. This can be alleviated with the construction of pilot- and demonstration-scale facilities.

Pilot- and demonstration-scale projects are key milestones for the commercialization of novel technologies. These facilities are not intended to generate revenue, but they sometimes require significant financial commitments. Pilot-scale biorefineries have capacities of less than 5 MT per day, and demonstration-scale facilities can operate at commercial production rates but are discontinued once operators obtain the necessary data. Industry has so far been reluctant to invest in these capital-intensive demonstration facilities. Unfortunately, there are important processing considerations that can only be tested at commercial scale.

Data from privately funded demonstration projects are almost never released to the general public. However, this data is crucial to help guide policy decisions that may affect the development of biorefinery technologies. Demonstration-plant data will drastically improve the quality of TEA studies, and conversely, TEA will improve in their ability to clarify the path from nascent technology to commercial product.

2.5.2 Combination of TEA and LCA

Researchers are combining TEA with life cycle analysis (LCA) to provide a comprehensive evaluation of biorefinery technologies (Hill *et al.*, 2006). These techniques share a symbiotic relationship in that they enhance findings from each discipline. TEA can quantify the economic costs

associated with environmental impacts, and LCA determines the environmental effects related to TEA assumptions.

LCA researchers estimate the environmental impacts associated with biorefinery operations. Sometimes, the environmental impacts can be readily quantified in economic terms – water treatment of process effluent, for example. It is much harder to determine the economic cost of other types of environmental impacts like those associated with global climate change. TEAs can help determine the proper incentives or penalties required to encourage or mitigate these environmental impacts.

System boundaries are an important consideration for both TEA and LCA. TEAs are typically confined to the boundaries of a specific process, but can extend to include global economic activity. LCA research on the other hand encourages the expansion of system boundaries to properly account for environmental impacts. Therefore there are important tradeoffs involved in combining both techniques. In general, data availability weighs heavily on the choice of system boundaries.

There is an increasing awareness of the environmental impacts of industrial activity. The long-term implications of commissioning biorefinery projects require careful study of both economic and environmental risks. Knowledge gained from future biorefinery projects will enhance our understanding of both risks if they are investigated in a concerted fashion.

2.5.3 Risk and uncertainty quantification

A major challenge for TEA and LCA studies is risk and uncertainty quantification. Industry employs economic risk, measured by indicators such as rate of return and net present value, to identify investment opportunities. Policy makers rely on LCA to estimate greenhouse gas emissions and resource use. Varying degrees of uncertainty underlie these measures. Therefore, research requires additional tools to understand the implications of these uncertainties.

Researchers employ an increasing number of techniques such as case studies, sensitivity analysis, and Monte Carlo simulations to improve uncertainty quantification in TEA and LCA studies. The need for uncertainty quantification is driven by uncertainties in model parameters, their interactions, and the outputs generated by these analyses.

Case studies are the most trivial approach to quantifying uncertainty and are not always recognized as such. However, careful selection of system scenarios can provide more than enough data to understand project risks. For example, case studies based on the extreme values of historical market prices for a given commodity could be enough to rule out a potential project. The drawback of case studies is that they provide minimal insight into the interactions between different model parameters.

Sensitivity analyses improve upon case studies by evaluating several points within a range of parameter values. Their key insight is the extent to which system outputs change based on different input assumptions. Sensitivity analyses that involve a large number of randomized model evaluations are known as Monte Carlo simulations. Monte Carlo simulations benefit from inexpensive computational resources that allow rapid model evaluations. Researchers employ Monte Carlo extensively in a wide range of fields to develop model probability distributions. Increasing model complexity has limited the use of this brute-force method because it would consume significant computational time and resources. Researchers continue to adopt powerful techniques to model, collect, and assess TEA data that are beyond the scope of this chapter.

These uncertainty quantification techniques help reduce risks from assumption bias and failure to consider adverse scenarios. However, they are not a substitute for robust models with sensible built-in assumptions.

2.5.4 System optimization and statistical techniques

There is a growing desire to optimize TEA models and understand the implications for real systems. Modern process modeling tools include optimization functions or can couple with stand-alone optimization software like IBM ILOG CPLEX Optimizer, Gurobi™, and GAMS among others. These tools allow researchers to systematically identify optimal operating parameters that meet certain constraints.

TEA models include parameters bounded by system constraints. For example, biorefineries include both technical (reactor temperature) and economic (minimum feedstock cost) constraints that need to be considered within the model. Within the bounds of the allowable parameters there are usually one or more function maxima or minima. In this regard, TEA systems are somewhat simpler than other mathematical models – the function space is well defined. The major challenges for optimization of TEA models are large, complex models with hundreds of parameters, and models that express extremely nonlinear behavior. Techniques that address both of these challenges are the subject of much research.

Researchers employ model surrogates or reduced order models (ROMs) to optimize large models that are either too complex or computationally expensive to evaluate. ROMs can significantly reduce the time required to optimize high-fidelity models at the risk of over-simplifying the problem. Therefore, several approaches have been proposed for the identification of ROM parameters and the evaluation of ROM accuracy.

The benefits of process optimization go beyond identifying optimal values. They also identify tradeoffs between differing objectives. These tradeoffs can be illustrated by a Pareto curve. Pareto curves describe the

incremental changes of a given objective value due to improving a second objective. For example, biorefineries commonly face a tradeoff between lowering process costs from the use of fossil fuels and increasing their overall environmental footprint.

These emerging trends suggest a bright future for techno-economic analysis study and its impact on the advancement of biorefineries. The study of demonstration-plant data, combination of TEA and LCA, evaluation of risk and uncertainty, and optimization of system models are fertile grounds for future research and development.

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