Chapter

12

Economics of Biorenewable Resources

12.1 Introduction

Market acceptance of new products depends upon the complex interplay of several factors including cost, physical properties, environmental performance, public policy, and cultural prejudices. This chapter focuses on the problem of manufacturing biobased products that are cost-competitive with products already produced from petroleum or other fossil resources. Although biobased products may look attractive from other perspectives, a company will have little incentive to develop them unless the enterprise is projected to be profitable.

Accurate cost forecasting is a difficult and time-consuming activity best left to the experts. However, *cost estimating* is a valuable skill that allows an engineer to obtain "ballpark" approximations of project costs. The goal is to obtain an estimate that is within +/− 30% of the actual cost if the enterprise were pursued. Such estimates are relatively easy to develop. Additional tools such as sensitivity analysis and uncertainty analysis can be employed to identify and mitigate the distortions that this cost range has on the final result, allowing the cost estimates to be employed as an important analytical methodology.

Two kinds of costs will be considered in this chapter: the cost of producing biorenewable resource feedstocks and the cost of manufacturing biobased products from these feedstocks.

12.2 Estimating the Cost of Feedstock from Biorenewable Resources

For the purpose of cost estimating, biorenewable resources are conveniently classified as either *processing residues* from urban areas, wood mills, or agricultural processing plants; *harvesting residues* from harvesting lumber or agricultural crops; or *dedicated energy crops*. Processing residues are highly concentrated, already

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having been transported to a central processing facility, and they are often considered to be waste products. Thus, they can often be acquired at low or even negative cost with minimal transportation cost (as demand for the waste product grows, however, its cost will also increase, potentially negating this benefit). Harvesting residues are also underutilized and represent additional income for producers if they are collected and sold as a biorenewable resource. These residues are more expensive than processing residues because they must be collected from fields and transported to a central processing facility. However, development of machinery that simultaneously collects agricultural residues while harvesting the primary crop could reduce costs. Dedicated energy crops are biorenewable resources grown specifically as feedstock for the production of biobased products. Unlike agricultural residues, dedicated energy crops must bear all the expenses of cultivation and harvest; thus, they are the most expensive of the biorenewable resources. On the other hand, both kinds of residues are limited in extent to existing areas of primary crop cultivation, while the cultivation of dedicated energy crops could be expanded significantly, as described in Chapter 4.

The cost of a biorenewable resource is related to the demand for the resource by a supply curve. Figure 12.1 is a generalized representation of a supply curve for the three kinds of biorenewable resources. The least expensive is processing residues, the price of which begins to rise sharply as the supply limit is approached. Note that the supply is relatively smaller than the other kinds of biorenewable resources. Because of additional collecting and harvesting expenses, the cost of harvesting residues is significantly higher than for processing residues. The supply, however, is substantially greater. Finally, the costs of dedicated energy crops are higher than the other kinds of biorenewable resources but climbs more gradually as the demand increases. The increasing price reflects the use of less productive land to supply the

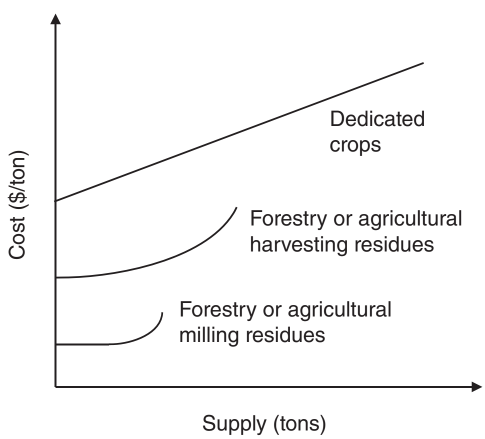

FIG. 12.1 Example of supply curves for different kinds of biorenewable resources.

Table 12.1 Availability and cost of potential US feedstocks

Feedstock	Production (10^6 Mg/year)	Price (2010 \$/Mg)
Corn	107	151
Potato	18	207
Sorghum	9	180
Sugar beets	32	67
Rice	11	122
Sugar cane	27	42
Agricultural Residues and Wastes		
Low cost	59	<40
Mid cost	143	<50
High cost	162	<60
Forest Residues and Wood Wastes		
Low cost	33	<20
Mid cost	79	<40
High cost	119	<80

Sources: Crop data from US Department of Agriculture (2013) *National Agricultural Statistics Service—Statistics by Subject.*; waste and residue data from US Department of Energy (2011) *U.S. Billion-Ton Update: Biomass Supply for a Bioenergy and Bioproducts Industry*, ORNL/TM-2011/224. 148–149.

additional demand. Note that the supply curve for dedicated energy crops extends much further than the other supply curves.

The cost of biorenewable resources is highly variable and dependent on local conditions of supply and demand. This is particularly true for the processing residues and wastes, and no effort will be made to develop a methodology for estimating their costs. Instead, Table 12.1 is included to provide an estimate of availability and cost of several kinds of residues and wastes along with a comparison of the cost of a few conventional row crops. The cultivation and harvesting of dedicated energy crops, on the other hand, is amenable to standardized cost estimating since information on "unit operations," such as planting, fertilizing, and harvesting, can be readily obtained from knowledgeable sources.

12.2.1 Unit Cost for Production of Annual Crops

This methodology focuses on *annual crops* such as corn or sweet sorghum, which are planted and harvested every year. The methodology can be easily adapted to estimating the cost of harvesting residues. The methodology consists of breaking down a production system into important expense categories and assigning a cost per hectare. As shown in Table 12.2, these expense categories include preharvest machinery, seed/cuttings, fertilizer, pesticides, crop insurance, interest on short-term loans, miscellaneous, harvest machinery, labor, land, and transportation. Expenses for each expense category allow for both variable costs and fixed costs. Variable costs depend on the extent of their usage. Things such as

Table 12.2 Cost of production for annual crop

Crop:				Yield (Mg/ha/year)		Date:
Production Method:				Market Price ($/Mg)		
			Expenses		Explanation	
			Variable ($/ha)	Fixed ($/ha)		
Preharvest Machinery					Plowing, disking, fertilizing, planting, cultivating, and spraying; variable expense is fuel and repair; fixed expense is capital charges	
	$/Unit	Unit/ha				
Seed/cuttings						
Fertilizer						
Nitrogen						
P_2O_5						
K_2O						
Lime						
Pesticides						
Herbicides						
Insecticides						
Crop Insurance						
Interest					Interest on preharvest fixed variable expenses	
Miscellaneous						
Harvest Machinery					Variable expense is fuel and repair; fixed expense is capital charges	
Harvest					May involve combining or mowing, raking, and baling or forage chopping depending on the type of crop	
Haul						
Dry						
Labor					Assumed to be hired labor, a variable expense	
Land					A fixed expense whether rented or financed	
Transportation					Set to zero when calculating "farm-gate" price of crop	
Total Fixed or Variable Expense						
Total Expense					Add variable and fixed expenses	
Unit Production Cost ($/Mg)					Divide total costs ($/ha/year) by yield (Mg/ha)	

seed/cuttings, fertilizer, and pesticides are variable costs. There are also fixed costs, which are invariant during the operation and include such things as land rental and taxes. Some cost categories have both fixed and variable costs, of which machinery expenses are the most prominent example. Variable costs of machinery include fuel for operating machinery and repair to maintain machinery. Fixed costs of machinery are primarily payment of interest and principal on loans used to purchase the machinery.

Preharvest machinery expenses include plowing, disking, planting, fertilizing, cultivating, and spraying. Harvest machinery expenses depend upon the kind of crop being harvested. Grain crops involve combining; hay crops involve a series of operations, including cutting, raking, and baling; forage crops are harvested with a forage chopper; and short-rotation woody crops involve specialized cutting and chipping machinery. Machinery expenses associated with several kinds of production operations on a hectare basis can be estimated from Table 12.3, which includes information on both variable and fixed expenses of machinery operation in the state of Iowa. These numbers do not include labor costs, which are estimated separately. More detailed information can be obtained from extension services of many land-grant universities.

The cost of seed and cuttings is calculated as the product of cost per unit of seed or cutting and units planted per hectare. The unit of seed or cutting is either the number of kernels, in the case of corn, the weight of seed, or the number of cuttings, in the case of short-rotation woody crops. The units planted per hectare for a particular crop depend upon climate and soil type. Both cost per unit and units planted per hectare can be estimated for several kinds of crops from Table 12.4. The cost of fertilizer and pesticides per hectare can be estimated from Table 12.5 for several kinds of crops. More detailed information for specific agricultural regions can be obtained from extension services of many land-grant universities.

Crop insurance protects a producer against lost income in case of catastrophic crop loss associated with damage from hail, wind, or flooding. Interest is the cost of money borrowed for purchase of seed and chemicals and other preharvest variable expenses. These are short-term loans for a period roughly equal to the time between planting and harvest of an annual crop. Financing of perennial crops requiring several growing seasons before harvest requires longer-term financing and more sophisticated cost analysis, as described in Section 12.2.2. Miscellaneous expenses may include property taxes or other expenses not accounted for in the other expense categories.

Labor rates are determined by adding up the time required to perform all preharvest and harvest operations and multiplying by the hourly wage of laborers. For many cropping systems, the total labor requirement has already been determined. Hourly wages may vary considerably depending on labor availability and the skill required for the operation.

Table 12.3 Machinery costs for crop production

	Expenses ($/ha)[a]	
	Fixed	Variable
Moldboard plow	22.23	27.17
Chisel plow	9.39	11.86
Chop stalks	12.60	14.08
Tandem disk	8.89	7.66
Offset disk	10.37	10.13
Peg tooth harrow	5.19	4.45
Sprayer/disk	8.89	8.15
Field cultivator	6.18	7.66
Bulk fertilizer spreader	4.45	4.20
NH_3 applicator	11.61	13.09
Chisel plow, NH_3 application	12.35	15.56
Grain drill	10.87	10.87
Broadcast seeder	7.16	4.69
Planter	14.82	13.34
No-till planter	16.30	15.31
No-till drill	16.30	16.06
Rotary hoe	3.95	2.96
Cultivator	4.69	5.43
Sprayer	4.94	4.94
Combine corn	50.88	28.16
Combine beans	40.51	21.98
Combine small grain	30.13	13.83
Haul grain (on farm)	0.04/bu	0.04/bu
Grain cart	14.08	8.15
Silage harvester	74.1	39.77
Haul silage	1.25/Mg	1.50/Mg
Rotary mower	15.31	11.12
Mower-conditioner	13.09	11.86
Rake	9.39	6.42
Large square baler	26.68	21.49
Round baler	26.92	21.49
Windrower	7.66	5.93
Haul round bales	2.10/Mg	3.65/Mg
Forage chopper	41.00	34.83

Source: Adapted from Duffy, M. *Estimated Costs of Crop Production in Iowa—2013*, Iowa State University Extension Publication 1712.
[a]Units are $/ha unless otherwise noted.

The cost of renting land or financing the purchase of land can account for more than half the cost of production. In the case of financed purchase of land, this expense is called a capital charge and represents annual payments of principal and interest on a long-term loan. For a loan on the principal amount P taken out at interest rate i to be paid back over a period of n years, the annual capital charge A_{CC} that would appear in this expense category is

$$A_{CC} = \frac{Pi(1+i)^n}{(1+i)^n - 1} \tag{12.1}$$

Table 12.4 Costs for seed and cuttings in crop production

	Unit	Unit Cost ($/unit)	Application (units/ha)
Seed/cutting			
Corn (following soybeans)	Mg	170	11.3
Corn (following corn)	Mg	198	10.4
Soybeans (GMO)	Mg	402	3.36
Soybeans (non-GMO)	kg	410	3.36
Alfalfa	Mg	122	9.9
Short-rotation woody biomass	cutting	0.1	7200

Sources: Data for agricultural cropping systems adapted from Duffy, M., *Estimated Costs of Crop Production in Iowa—2013*, Iowa State University Extension Publication 1712; data for forestry cropping systems adapted from Wiltsee, G. and Hughes, E. (1995) Biomass energy: cost of crops and power. *Electric Power Research Institute Final Report TR-102107*, Vol. 2, October.

Unit cost of production is calculated as the total expenses ($/ha) divided by the crop yield (Mg/ha). An important expense neglected in this analysis is federal income tax that must be paid on the profits resulting from the enterprise. However, this tax is often ignored in calculating unit cost of production since it depends on all income streams for a tax-paying individual or corporation and is complicated by various depreciation allowances, accounting methodologies, and agriculture-specific tax credits. Income tax will be accounted for in the cash-flow analysis described in Section 12.2.2 for estimating unit cost of production for perennial crops.

Table 12.6 provides a cost projection for corn grown in Iowa in 2013. This analysis assumes conventional tillage following a crop of corn in the previous

Table 12.5 Costs for chemicals in crop production

			Application (units/ha)				
	Unit	Unit Cost ($/unit)	Corn following corn	Corn following soybeans	Soybeans (GMO)	Alfalfa	SRWC[a]
Fertilizer							
Nitrogen	kg	1.28	209	147	0	0	137
Phosphate	kg	1.06	70	76	45	39	See note
Potash	kg	1.10	56	61	84	140	See note
			Unit Cost ($/ha)				
Pesticides			Corn following corn	Corn following soybeans	Soybeans (GMO)	Alfalfa	SRWC[a]
Herbicide			68.50	61.75	41.50	37.30	85.00
Insecticide			46.93	0	0	0	See note

Sources: Data for agricultural cropping systems adapted from Duffy, M. *Estimated Costs of Crop Production in Iowa—2013*, Iowa State University Extension Publication 1712; data for forestry cropping systems adapted from Wiltsee, G. and Hughes, E. (1995) Biomass energy: cost of crops and power. *Electric Power Research Institute Final Report TR-102107*, Vol. 2, October 1995.

[a] Short-rotation wood crop—nitrogen applied every third year; other fertilizers dependent on soils; herbicide is applied during establishment with occasional follow-up at $38/ha; insecticide applied as needed at $2.15/ha.

Table 12.6 Example of cost of production for corn crop

Crop: Corn following corn			Yield (Mg/ha/year): 10.4[a]	Date: 2013
Production Method:	Chisel plow, tandem disk, apply N, field cultivate, plant, cultivate, and spray		Market price ($/Mg) $276[b]	
			Expenses	
			Variable ($/ha)	Fixed ($/ha)
Preharvest Machinery			55.82	58.54
	$/Unit	Unit/ha		
Seed	$3.64/1000 k	74 100	269.47	
Fertilizer				
Nitrogen	$1.28/kg	209	266.46	
Phosphate	$1.06/kg	70	73.51	
Potash	$1.10/kg	56	61.75	
Lime			23.76	
Pesticides				
Herbicides			61.75	
Insecticides			46.93	
Crop Insurance			60.52	
Interest			33.39	
Miscellaneous			22.23	
Harvest Machinery				
Harvest			28.16	51.03
Grain cart			8.15	6.70
Haul			16.30	16.30
Dry			78.25	20.38
Labor				86.23
Land (cash rent equivalent)				−681.72
Transportation			–	–
Total variable or fixed expense			1119.48	932.35
Total expense			2051.83	
Unit Production Cost ($/Mg)			198.00	

Source: Data adapted from Duffy, M., *Estimated Costs of Crop Production in Iowa—2013*, Iowa State University Extension Publication 1712.

[a]Equivalent to 165 bushels per acre.

[b]Equivalent to $7.00 per bushel.

year, which affects the amount of field preparation. Note that the largest variable expenses after seed are nitrogen (\$266.46/ha) and phosphate fertilizer (\$73.51/ha). However, rental of land, a fixed expense, is the most important factor determining the cost of production, representing one-third of the cost of producing corn.

12.2.2 Unit Cost for Production of Perennial Crops

Perennial crops, such as hybrid poplar and switchgrass, have planting/harvest cycles that span several years and may show dramatic differences in production expenses and revenues from one year to the next. In this case, calculating production costs is more complicated because capital investment is required early in the project while significant revenue may not be generated for 2 or 3 years, in the case of switchgrass, or as long as 7 years, in the case of dedicated woody crops. Furthermore, meaningful analysis requires an accounting of the time value of money, which recognizes that a dollar spent or earned today is worth more than the same dollar in the future as a result of inflation and investment opportunities for money in the present.

The relationship between the future value, FV, and present value, PV, of a sum of money compounded annually at an interest rate, i, for a total of n years is

$$\mathrm{FV} = \mathrm{PV}(1 + i)^n \tag{12.2}$$

For example, \$100 invested today at 5% for 2 years will return:

$$\mathrm{FV} = \$100 \times (1 + 0.05)^2 = \$110 \tag{12.3}$$

Similarly, inflation at 5% per annum makes \$100 worth of merchandise today cost \$110 in 2 years.

Discounting is the opposite of compounding: the present value of a sum of money to be spent or received in the future is reduced according to

$$\mathrm{PV} = \frac{\mathrm{FV}}{(1 + i)^n} \tag{12.4}$$

where i is now referred to as the discount rate. Thus, if the discount rate is 5% per annum, \$100 to be spent 2 years hence has a present value of only

$$\mathrm{PV} = \frac{\$100}{(1 + 0.05)^2} = \$91 \tag{12.5}$$

Since the present value of money to be spent in the future declines with increasing interest rate and number of years into the future, the importance of accounting for the time at which money is spent or received is evident.

Cash-flow analysis is a method for accounting for the time value of money. The procedure is quite simple. For each year, all inflows of cash are subtracted from all outflows of cash to obtain an annual cash flow. In the case of crop production, inflows and outflows are conveniently expressed on a per hectare basis.

The production cost procedure developed for annual crops has been modified in Table 12.7 to allow an accounting of production costs of perennial crops over several years using the cash-flow method. Note that the table still includes the major expense categories previously considered, but columns have been added for fixed and variable expenses for every year of the enterprise (assumed to be five in Table 12.7 but possibly even longer for some short-rotation woody crops). Furthermore, additional rows are included for calculating cash flow, discounted cash flow, and net present value (NPV).

Inflows consist of annual revenues A_R from the sale of products or coproducts. These revenues are calculated from market price and yield of the crop:

$$A_R\ (\$/\text{ha}) = \text{Market price}\ (\$/\text{Mg}) \times \text{Yield}\ (\text{Mg/ha}) \tag{12.6}$$

Prices vary considerably from one year to the next, and yields are strongly dependent on soil type, geographic location, and weather, so care should be taken in assigning values for the purpose of cost estimating.

Outflows are operating expenses A_{OE}, owner's capital invested in the purchase of equipment or property A_{CI}, and federal income tax A_{IT}. These expenses are subtracted from revenues to yield net cash flow A_{CF}:

$$A_{CF} = A_R - (A_{OE} + A_{CI} + A_{IT}) \tag{12.7}$$

Note that capital invested is money provided by owners of the enterprise, whereas capital charges, an expense category accounted for under operating expenses, are the annual interest and principal payments the owners make toward retiring a loan on the purchase of land and equipment.

Federal income taxes are assessed as a certain percentage of the difference between revenues A_R and certain allowable expenses and deductions. Allowable expenses include all the previously detailed operating expenses except for repayment of principal on loans, A_P.

Allowable deductions are depreciation valuations on capital equipment. Depreciation is an important tax incentive based on the idea that equipment purchased for an enterprise "wears out" over time. Depreciation allows investors to exclude from taxation the loss in value of their original capital investment. Although different rules for calculating depreciation have been devised, straight-line depreciation is commonly employed. The annual amount of depreciation A_D by this method is the difference in fixed capital cost C_{FC} and salvage value S of the equipment divided by the depreciating time period t_D, usually taken as the useful life of the

Table 12.7 Cost of production for perennial crop

Crop:				Yield (Mg/ha/year):							Date:
Production Method:				Market Price ($/Mg)							
	Expenses ($/ha)										
Year:	1		2		3		4		5		
	Fixed	Variable	Fixed	Variable	Fixed	Variable	Fixed	Variable	Fixed	Variable	
Capital Investment, A_{CI}											Owner's capital to purchase land or equipment
Preharvest Machinery											Fixed expense includes interest A_I and principle A_P on loans
Seeds/cuttings											
Fertilizer											
Pesticides											
Crop Insurance											
Interest											
Miscellaneous											
Harvest Machinery											Fixed expense includes interest A_I and principle A_P on loans
Labor											
Land											If land is financed, includes interest A_I and principle A_P on loans
Total Fixed, A_{FE} or Variable, A_{VE} Expenses											
Total Operating Expenses, A_{OE}											$= A_{FE} + A_{VE}$
Total Revenue, A_R											= Market price × yield
Federal Income Tax, A_{IT}											$=$ Tax rate $\times (A_R - (A_{OE} - A_P) - A_D)$
Cash Flow, A_{CF}											$= A_R - (A_{OE} + A_{CI} + A_{IT})$
Discounted Cash Flow, A_{DCF}											$= A_{CF}/(1 + r)^n$
Net Present Value, NPV											$= \Sigma A_{DCF}$

equipment or as otherwise allowed by tax laws (real estate and working capital (WC), consisting of start-up inventory for a plant, cannot be depreciated):

$$A_{\mathrm{D}} = \frac{C_{\mathrm{FC}} - S}{t_{\mathrm{D}}} \tag{12.8}$$

Thus, the calculation of income taxes is made by the following relationship:

$$A_{\mathrm{IT}} = \text{tax rate} \times (A_{\mathrm{R}} - (A_{\mathrm{OE}} - A_{\mathrm{P}}) - A_{\mathrm{D}}) \tag{12.9}$$

Tax rates are strongly dependent on the income generated by the enterprise. Small agricultural enterprises may only be taxed at 10–25%, whereas large enterprises have been historically taxed at 35–40%.

Cash flows must be discounted for the year in which cash is spent or earned. Annual discounted cash flow A_{DCF} is calculated for each year n:

$$A_{\mathrm{DCF}} = \frac{A_{\mathrm{CF}}}{(1+i)^n} \tag{12.10}$$

The discount interest rate to use in this equation is one appropriate to the investment goals of the owners. It normally accounts for both the inflation rate f of money for the period of investment and a real rate of return r. This so-called nominal rate of return i is obtained as the geometric mean of the inflation rate and real rate of return:

$$1 + i = (1 + f) \times (1 + r) \tag{12.11}$$

An excellent approximation to this relationship is

$$i = f + r \tag{12.12}$$

Summing over all the annual discounted cash flows yields the NPV of the enterprise:

$$\mathrm{NPV} = \sum_n A_{\mathrm{DCF}} \tag{12.13}$$

Clearly, a positive NPV at the end of the investment period indicates an investment that exceeds the desired discount rate, while a negative value indicates one that does not achieve the desired rate. If the discount rate is adjusted to achieve an NPV of exactly zero, the resulting rate is called the internal rate of return (IRR). Alternatively, if the market price is adjusted to achieve an NPV of exactly zero, the

Table 12.8 Simplified example of discounted cash flow analysis for perennial crop production

Crop: Perennial Grass	Yield (Mg/ha): 12	Market Price ($/Mg): $45				
Discount rate: 10%						
Year:		1	2	3	4	5
Capital invested	A_{CI}	($700)	$0	$0	$0	$0
Expenses	A_E	($300)	($250)	($250)	($250)	($250)
Revenue	A_R = yield × price	$0	$540	$540	$540	$540
Annual cash flow	$A_{CF} = A_R - A_{CI} - A_E$	($1000)	$290	$290	$290	$290
Discounted annual cash flow	$A_{DCF} = A_{CF}/(1 + i)^n$	($909)	$240	$218	$198	$180
Net present value	$NPV = \Sigma A_{DCF}$					($73)

resulting market price represents the production cost or minimum selling price (MSP) of the crop assuming the specified discount rate. This second approach is particularly useful in estimating the cost of feedstocks from biorenewable resources grown as perennial crops. It can also be employed to calculate the cost of producing biobased products over the life of a manufacturing facility.

A simplified example of discounted cash flow analysis for a perennial crop is presented in Table 12.8. The crop is assumed to be a perennial grass that is planted in the first year and harvested annually in the second through fifth years of the enterprise. Capital invested in the first year, for the purchase of land, is $700/ha (dollars enclosed in parentheses represent negative cash flows). The discount rate is chosen to be 10%, which represents the expected IRR of investors in the enterprise. Annual expenses, which are not detailed in this example, are assumed higher in the first year than subsequent years because of the cost of planting and chemical treatment (herbicide and fertilizer). Income taxes are ignored to simplify the analysis. Revenue, which starts in the second year, of $540/ha is based on a constant market price of $45/Mg and crop yield of 12 Mg/ha (obviously, both price and yield will vary from year to year in a real enterprise).

Annual cash flow in the first year is negative because no crop is harvested during the establishment year. Cumulative revenue in subsequent years must be high enough to not only offset the expenses of those years but pay for the annual expense and capital investment of the first year. To get a realistic appraisal of the time value of money, the discounting factor of $(1 + i)^{-n}$ is applied to the cash flow of the nth year to derive discounted cash flows for each year. Table 12.8 shows that revenue in early years is more valuable than revenue in later years, while expenses in early years are more costly than expenses in later years.

The cash flows over the 5 years are summed to yield the NPV of the enterprise after 5 years, which in this example is −$73/ha. Thus, the enterprise has not returned the investors their expected return of 10% per annum. In this simple

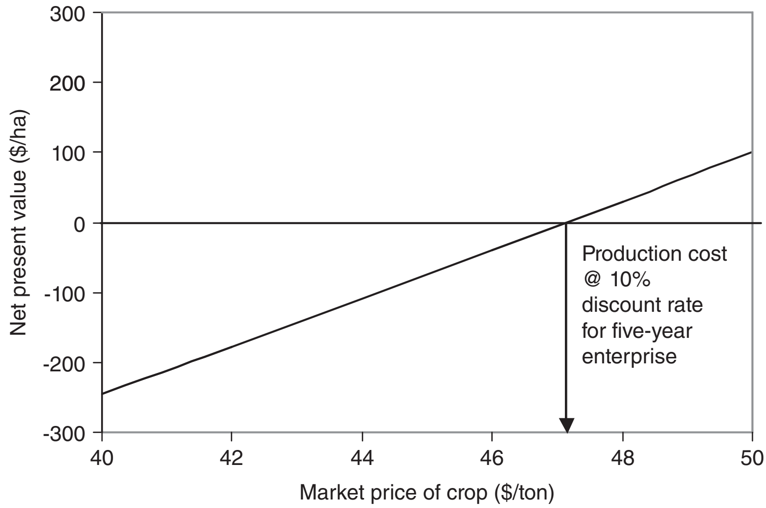

Fig. 12.2 Estimating unit cost of production for a perennial crop using cash-flow analysis (based on data in Table 12.8).

example, we can see that one additional year of harvesting would yield an NPV that was positive, unless, of course, the perennial grass had to be replanted after 5 years.

Production cost of this perennial grass over 5 years is found by plotting NPV of the enterprise after 5 years vs. assumed market price of the crop, as shown in Figure 12.2. When the market price reaches approximately $47, NPV becomes zero, representing the cost of producing the crop in the case of a 10% annual rate of return.

Table 12.9 gives estimated costs of producing several lignocellulosic feedstocks. While production and harvesting of lignocellulosic biomass has been historically limited to the pulp and paper industry, the discovery that they can be processed into high-value biofuels and bioproducts has made them attractive to both producers and manufacturers due to their abundance in nature relative to conventional row crops. Furthermore, some types of lignocellulosic feedstock can be grown on marginal land not suitable for conventional row crop production, thereby both expanding productive acreages while mitigating the food and feed crop-displacement concerns that have risen from the use of corn and soybeans as biofuel feedstocks.

Discounted cash flow analysis is an essential tool for estimating unit cost of production for perennial crops. It also is a powerful technique for estimating costs of annual crops, even for relatively constant revenues and expenses, if the time value of loans or invested capital is to be accounted for over the life of the loan or investment period. Discounted cash flow analysis is also very important in estimating costs of manufacturing biobased products from biorenewable resources.

Table 12.9 Estimated US willing to accept price for candidate lignocellulosic feedstock

Region and Species	Price ($/Mg)
Stover	92
Alfalfa	118
Switchgrass (Midwest)	133
Switchgrass (Appalachia)	100
Switchgrass (South Central)	98
Miscanthus (Midwest)	115
Miscanthus (Appalachia)	105
Wheat straw	75
Short rotation woody biomass	89
Forest residues	78

Source: Adapted from Committee on Economic and Environmental Impacts of Increasing Biofuels Production (2011). *Renewable Fuel Standard: Potential Economic and Environmental Effects of U.S. Biofuel Policy*, pp. 125. Washington, DC: The National Academies Press.

12.3 Estimating Unit Cost for Manufacturing Biobased Products

There are two important quantities to determine in economic analysis of a process: capital cost and operating cost. *Capital cost* is the amount of money to build a plant or facility and includes all equipment and labor associated with installation of the equipment. *Operating cost* represents the annual expenses to keep a plant or facility in full production. It includes costs of feedstock and fuel, labor to operate the plant, and payment of principle and interest on loans (capital charges). Operating cost is often expressed as *production cost*, which is annual operating cost divided by annual production output.

The first step in cost estimation is to design the process to be employed in the plant or facility, whether a cellulosic ethanol facility or a fast pyrolysis facility to produce renewable gasoline and diesel fuel. The design should include a flow sheet that quantifies temperatures, pressures, and balances of mass and energy through the process. Software packages such as Aspen Plus® and CHEMCAD are available for constructing and optimizing process models capable of simulating the operations of biorenewable pathways and facilities. This information is key in specifying the cost of equipment to be purchased and installed and raw materials and utilities to be consumed in the operation of the plant. After this is done, capital costs and operating costs can be estimated.

12.3.1 Capital Costs

Capital costs are broken down into four major categories: direct costs, indirect costs, project contingency, and working capital. Each of these major categories can be broken down into subcategories to yield a summary of capital costs.

Equipment Costs

Equipment (or direct) costs include the purchase price of equipment to be installed, cost of materials required for the installation and cost of the installation itself.

Total Purchased Equipment Cost The cost of equipment is usually expressed in terms of “free onboard” (f.o.b.), which is the price paid to a supplier to crate and place equipment onboard a freight carrier. The f.o.b. equipment cost requires an accounting of freight expenses. These equipment costs can be determined by calling various suppliers and obtaining informal or formal quotes. Most will supply catalogs upon request and many maintain web sites, which may or may not include price information. A good way to identify suppliers is the Thomas Register, which is available in most technical libraries and on the Internet.

Equipment cost estimation for new technologies or complex projects can be done more quickly with tabulations found in the literature [1, 2, 3, 4, 5] or in process modeling software such as Aspen Plus. These are usually presented as charts of *purchased equipment cost (f.o.b.)* vs. an appropriate sizing parameter (volume, heat transfer area, flow rate, power, etc.).

Very frequently, cost data are not readily available for the particular size of equipment or facility of interest, and a method for scaling the cost to the appropriate size is required. However, assuming that costs of equipment are linearly related to the size of the equipment will almost always produce large errors. The *principle of economies of scale* predicts that capital costs escalate proportionally slower than the size of the facility; hence, the unit cost of a product generally decreases as the facility becomes larger.

A rational basis of comparison must scale capital costs to realistic equipment size. Recognizing that capacity of a simple piece of equipment like a water tank increases with volume (i.e., as the cube of the characteristic dimension) and that the cost of the tank, for a given wall thickness, increases with the surface area of metal plate used in its construction (i.e., as the square of the characteristic dimension), it follows that the cost of the tank increases as the two-thirds power of capacity. This idea is expressed as the following simple scaling law [3]:

$$C_{\mathrm{p,s}} = C_{\mathrm{p,b}} \left(\frac{S_{\mathrm{s}}}{S_{\mathrm{b}}} \right)^{n} \tag{12.14}$$

where

$C_{\mathrm{p,s}}$ = predicted cost of the specified equipment
$C_{\mathrm{p,b}}$ = known cost of the baseline equipment
S_{s} = size of the specified equipment
S_{b} = size of the baseline equipment
n = economy of scale sizing exponent (less than unity)

Table 12.10 Unit costs and scaling exponents for various kinds of plant equipment

Device	Sizing Parameter	Unit	Unit Cost[a]	Sizing Exponent
Process furnaces	Heating rate	kW	$982	0.85
Direct-fired heaters	Heating rate	kW	$88	0.85
Shell and tube heat exchangers	Heat transfer area	m^2	$2909	0.65
Process vessel (vertical)	Volume	m^3	$7273	0.71
Process vessel (horizontal)	Volume	m^3	$7515	0.6
Pump and driver	Flow rate × pressure head	m^3 kPa/min	$424	0.52
Compressor and driver	Power	kW	$6424	0.75
Agitators (propeller)	Power	kW	$2545	0.5
Air dryers	Volumetric flow rate	m^3/min	$9212	0.56
Blowers and fans	Volumetric flow rate	m^3/min	$96	0.68
Blenders	Volumetric flow rate	m^3/min	$33 939	0.52
Boilers (100 kPa)	Mass flow rate steam	kg/h	$3758	0.5
Boilers (4000 kPa)	Mass flow rate steam	kg/h	$5212	0.5
Centrifuges	Diameter	m	$76 362	1
Conveyer belt (0.6 m width)	Length	m	$7273	0.65
Conveyer bucket (30 tph)	Length	m	$3030	0.65
Conveyer screw (0.3 m dia.)	Length	m	$4364	0.8
Crushers (pulverizer)	Mass flow rate	kg/h	$4242	0.35
Crystallizers (forced circulation)	Mass flow rate	tpd	$52 120	0.55
Dryers (rotary, direct)	Volume	m^3	$19 394	0.42
Dryers (rotary, vacuum)	Volume	m^3	$43 635	0.69
Duct work, shop-fabricated, aluminum	Length	m	$65	0.55
Duct work, shop-fabricated, galvanized	Length	m	$97	0.55
Duct work, shop-fabricated, stainless steel	Length	m	$182	0.55
Evaporator (forced circulation)	Area	m^2	$193 935	0.7
Filter (plates and press)	Area	m^2	$8242	0.58
Filter (rotary drum)	Area	m^2	$38 787	0.63
Hoppers (conical)	Volume	m^3	$70	0.68
Mills (ball)	Mass flow rate	tph	$3636	0.65
Mills (hammer)	Mass flow rate	tph	$3394	0.85
Screens (vibrating)	Area	m^2	$21 818	0.58
Storage tanks	Volume	L	$1055	0.3

Sources: Adapted from Guthrie, K.M. (1969) Data and techniques for preliminary capital cost estimating. *Chemical Engineering*, 76, 114–142. except for unit cost and sizing exponent for dryers, which is adapted from Ulrich, G.D. (1984) *A Guide to Chemical Engineering Process Design and Economics*. New York: Wiley.; all data adjusted to 2010 dollars.

[a]Special materials of construction, operation at elevated pressures, and other factors may increase these costs.

The economy of scale sizing exponent diverges from the theoretical two-thirds value depending on the kind of equipment and sometimes on the size range of the equipment. This factor is reasonably well known from industrial practice for a variety of parts and equipment; these can be used to estimate overall costs of systems made up of such parts and equipment. Table 12.10 includes unit costs for several kinds of process equipment, adjusted to 2010 dollars, along with corresponding sizing exponents for scaling the equipment to other sizes. Keep in mind that special materials of construction, such as stainless steel, or operation at elevated pressures or other special circumstances may substantially increase equipment costs compared to the values presented in Table 12.10. In these cases, more detailed tables, such as found in Reference 1, should be consulted to obtain more accurate cost estimates.

> **Example:** A boiler is to be purchased to generate low-pressure steam (100 kPa). What is the f.o.b. cost for a boiler with 1×10^6 kg/h steam capacity? What would be the cost of a replacement pump and driver for this boiler?

From Table 12.10 is obtained a unit cost of \$3758 for a low-pressure boiler with 1 kg/h of steam flow. Linear scaling would suggest the desired steam capacity would cost:

$$\frac{\$3758}{\text{kg/h}}(1 \times 10^6\ \text{kg/h}) = \$3.8\ \text{billion}$$

Fortunately, economies of scale result in a considerably smaller escalation of price with increasing equipment size. Also from Table 12.10 is obtained a sizing exponent of 0.5. Substituting this information into Equation 12.14 yields:

$$\begin{aligned} C_\text{p}(1 \times 10^6\ \text{kg/h}) &= C_\text{p}(1\ \text{kg/h})\left(\frac{1 \times 10^6}{1}\right)^{0.5} \\ &= \$3758 \times 1000 \\ &= \$3.8\ \text{million} \end{aligned}$$

The replacement pump must be able to provide 1×10^6 kg/h of liquid water flow pressurized to 100 kPa. Note from Table 12.10 that the sizing parameter for pumps with drivers is the product of volumetric flow rate (in cubic meters per minute) and pressure head (in kilopascal). For the specified pump, the sizing parameter is

$$\begin{aligned} \text{Volumetric flow rate} \times \text{Pressure head} &= \frac{1 \times 10^6}{1 \times 10^3}\frac{\text{kg/h}}{\text{kg/m}^3}\left(\frac{1\ \text{h}}{60\ \text{min}}\right) \times 100\ \text{kPa} \\ &= 1667\ \text{m}^3\ \text{kPa/min} \end{aligned}$$

For this pump and driver the unit cost is \$424 and the sizing exponent for this pump is 0.52; thus, Equation 12.14 yields the replacement price for the boiler pump to be

$$C_p(1667\ \text{m}^3\ \text{kPa/min}) = C_p(1\ \text{m}^3\ \text{kPa/min}) \left(\frac{1667}{1}\right)^{0.52}$$
$$= \$424 \times 47.4$$
$$= \$20\ 098$$

Scaling relationships can also be applied to overall systems but with diminishing accuracy as the system becomes more complex. For many energy and chemical process plants, a reasonable estimate for n is 0.6, which yields the so-called "six-tenth rule" [3].

The extensive cost charts found in the literature were developed from prices effective in a particular year. Inflation can greatly increase the cost of equipment over the course of a few years and must be accounted for in estimating current equipment costs. This can be done with the relationship:

$$C_{p,c} = C_{p,p}\left(\frac{I_c}{I_p}\right) \tag{12.15}$$

where

$C_{p,c}$ = inflation-adjusted cost of equipment in current year
$C_{p,p}$ = known cost of equipment in a previous year
I_c = inflation index factor for current year
I_p = inflation index factor for the previous year in which equipment cost is known

Inflation index factors are available for different categories of equipment vs. year from a variety of sources. The Marshall and Swift (M&S) equipment index can be obtained from recent issues of *Chemical Engineering Magazine* or *The Oil and Gas Journal*. Alternatively, the consumer price index prepared by the US Bureau of Labor Statistics can be used as an estimate of inflation index factors for all classes of equipment, as given in Table 12.11.

Materials of Installation and Labor of Installation Installation of equipment can require considerable materials and labor: concrete and steel for an installation pad and support structure; electric wiring and control panels for motors; and piping and valves for water, gas, and steam utilities are among some of the more common items. Counting up all these costs represents considerable effort. Fortunately, *installation factors* have been determined for costs associated with installation of industrial equipment [1, 2, 5].

Installation factors represent the sum of different categories of installation expenses. Table 12.12 presents a range of installation factor categories and their respective values as developed by Reference 5. Each value operates as a percentage

Table 12.11 Inflation index factor based on the Consumer Price Index as published by the US Bureau of Labor Statistics[a]

Year	Inflation Index Factor	Year	Inflation Index Factor
1955	1	1984	3.88
1956	1.02	1985	4.02
1957	1.05	1986	4.10
1958	1.08	1987	4.25
1959	1.09	1988	4.42
1960	1.11	1989	4.64
1961	1.12	1990	4.89
1962	1.13	1991	5.09
1963	1.14	1992	5.25
1964	1.16	1993	5.40
1965	1.18	1994	5.54
1966	1.21	1995	5.70
1967	1.25	1996	5.87
1968	1.30	1997	6.00
1969	1.37	1998	6.10
1970	1.45	1999	6.23
1971	1.51	2000	6.44
1972	1.56	2001	6.62
1973	1.66	2002	6.73
1974	1.84	2003	6.88
1975	2.01	2004	7.06
1976	2.13	2005	7.30
1977	2.27	2006	7.54
1978	2.44	2007	7.75
1979	2.71	2008	8.05
1980	3.08	2009	8.02
1981	3.40	2010	8.15
1982	3.61	2011	8.41
1983	3.73	2012	8.59

Source: US Bureau of Labor Statistics (http://www.bls.gov/cpi/home.htm, accessed September 16, 2013).
[a]Inflation factors are normalized to the year 1955.

of the piece of equipment's purchased cost; for example, the cost of the piping required to install a piece of equipment is calculated as 10% of the equipment's purchased cost. The sum of these individual factors represents the full costs associated with equipment installation:

$$\text{TIC} = \text{TPEC} \times \text{TIF} \tag{12.16}$$

where TIC represents the total installed costs (i.e., the full cost of the purchased and installed equipment), TPEC represents the total purchased equipment costs, and TIF represents the total install factors. The sum of the individual installation factors can vary based on the type of facility considered and the expert opinion of the analyst, although a TIF of between 2.47 and 3.02 is common in the literature on biorenewable facilities.

Table 12.12 Methodology for capital cost estimation

Parameter	Assumption
TPEC	100%
Purchased equipment installation	39% of TPEC
Instrumentation and controls	26% of TPEC
Piping	10% of TPEC
Electrical systems	31% of TPEC
Buildings (including services)	29% of TPEC
Yard improvements	12% of TPEC
Service facilities	55% of TPEC
Total Installed Equipment Cost (TIEC)	TPEC × sum of installation factors (302%)
IC	TPEC × sum of IC factors (89%)
Engineering	32%
Construction	34%
Legal and contractors fees	23%
Total Installed Equipment and Indirect Costs	TEIC + TIC
Contingency	(TEIC + TIC) × 20%
FCI	(TEIC + TIC + contingency) × LF[a]
Working Capital (WC)	15% of FCI
Land Use	6% of TPEC
TPI	FCI + WC + Land

Source: Adapted from Peters, M., Timmerhaus, K., and West, R. (2002) *Plant Design and Economics for Chemical Engineers*. New York: McGraw-Hill.
[a]Location factor.

Example: Calculate the total cost of installing the low-pressure boiler of the previous example.

The purchased equipment cost of the boiler was estimated to be \$3.8 million in the previous example. From Table 12.12, the TIF is 3.02. Thus, TIC is

$$\text{TIC} = \text{TPEC} \times \text{TIF} = \$3\ 750\ 000 \times 3.02 = \$11\ 325\ 000$$

Thus, the cost to acquire and install the boiler is 202% higher than the purchased cost of the boiler.

Some references categorize the individual installation factors according to specific equipment type [6]. The "hand factors" methodology employs specific installation factors for eight categories of equipment, such as heat exchangers and pumps (Table 12.13). Multiplying the purchased cost of the equipment with the appropriate hand factor yields its installed cost. The TIEC is calculated by doing this for all purchased equipment and summing across the total results.

The "module factors" methodology expands upon the hand factors methodology by employing specific installation factors for 60 different equipment categories. The module factors divide many of the hand factor categories into subcategories,

Table 12.13 Hand factors for different equipment types

Equipment Type	Factor
Fractionating columns	4
Pressure vessels	4
Heat exchangers	3.5
Fired heaters	2
Pumps	4
Compressors	2.5
Instruments	4
Miscellaneous equipment	2.5

Source: Adapted from Brown, T.R. (2000) Capital cost estimating. *Hydrocarbon Processing*, 79(10), 93–100.

providing installation factors for multiple types of heat exchangers and pumps. The TIEC calculation for the module factor methodology is completed in the same manner as described for the hand factor methodology.

Indirect Costs

Indirect costs (IC) are expenses associated with the construction of a plant or facility that cannot be characterized as equipment, materials, or labor. The three most common IC are categorized as: *engineering expenses*; *construction overhead*; and *legal and contractors' fees*. The combined cost of *legal and contractors' fees* C_{LCF} can be estimated to be 23% of TPEC for projects in the United States. *Construction overhead* cost C_O represents such things as fringe benefits on labor (heath insurance, sick leave, vacation and holiday pay, retirement benefits); so-called burden on payroll (social security taxes, unemployment insurance, workmen's compensation); salary and benefits for supervisory personnel; rental of construction machinery and purchase of small tools; and site cleanup upon completion of a project. It can be estimated to be 34% of TPEC. *Engineering expenses* C_E include salaries and benefits for design and project engineers, office expenses, and associated overhead. It can be estimated to be 32% of TPEC.

Total direct and indirect costs (TDIC) represents all direct and indirect expenses associated with purchase and installation of a piece of equipment (TPEC + IC). *TDIC* for auxiliary facilities like complete power plants or wastewater treatment plants are sometimes tabulated. More frequently TDIC is not directly tabulated and these must be determined by estimating the expenses associated with equipment installation.

Contingency

An additional cost associated with an engineering project is *contingency cost*. Contingency refers to unexpected expenses on a project (weather-related delays, construction errors, poor estimation of costs, etc.) and is estimated to be 20% of TDIC. Note that a well-managed project would consume little of the contingency, which then becomes profit for the construction company.

The sum of TDIC and contingency is the fixed capital investment (FCI). FCI represents the full cost of the facility that can be depreciated and includes the purchased equipment costs, installation costs, IC, and contingency. Many equipment costs provided by databases such as Aspen Plus are based on prevailing costs in the US Gulf Coast region due to the large number of chemical engineering facilities located there. If the modeled facility is located elsewhere, FCI is multiplied by a location factor (LF) to reflect different prevailing costs in other regions and countries. This step is particularly important when the modeled facility is located in a region or country without an established refining industry, as much of the equipment will not be available domestically and will incur higher costs than in the US Gulf Coast as a result. Such a scenario is possible for a biorenewable facility, as access to petroleum reserves (and therefore a refining industry) is not a predictor of access to biomass feedstock. Capital cost LFs are available in the forms of the Richardson International Construction Factors Manual™ and the ENR 20-City Construction Cost Index.

Two additional capital costs frequently accounted for are WC and land. WC represents the cash and other liquid assets available to the facility to finance its day-to-day operations. It is estimated to be 15% of FCI. Land represents the cost of purchasing the land on which the facility is to be built and is estimated to be 6% of TPEC. Neither WC nor land is accounted for in FCI because neither is treated as depreciable assets, unlike the other capital costs. WC is a short-term asset and does not lose value through use (note that this is different from the loss of value occurring due to inflation). Land is also assumed to retain its full value through the lifetime of the facility. While neither cost is accounted for in FCI, they are both added to FCI to calculate the total project investment (TPI). TPI represents the full financial outlay required for the construction of a facility, and most capital cost estimates refer to TPI rather than FCI as a result.

12.3.2 Operating Costs

Once a facility is constructed, funds are required to ensure its continuous operation. Like capital costs, operating costs include direct costs and IC. In addition, there are *capital charges* that represent payments on loans secured to construct the plant. These costs are typically calculated on an annual basis, although a quarterly basis can also be used. Once the total operating cost is determined ($/year), it is divided by the *annual production output* (units/year) to determine the *annual production cost* ($/unit).

These various costs are conveniently tabulated in a *Summary of Operating Costs*, as illustrated in Table 12.14. At the top of the table is listed the *FCI* for the project,

Table 12.14 Summary of operating costs

FCI		Excludes Working Capital and Land
Working capital (WC)		15% of FCI
Land		6% of TPEC
TPI		Sum of FCI, WC, and land
Plant capacity factor (f_0)		Fraction of year that facility operates
Production output (units/year)		Annual production in kilowatts, gallons, etc. (adjusted to account for capacity factor)
	Cost ($/year)	Description
Variable cost		
Raw materials		Calculated as: $\$/\text{kg} \times \dot{m}\ (\text{kg/s}) \times 31.5 \times 10^6\ \text{s/year} \times f_0$
By-product credits		Value enclosed in parentheses and subtracted from other costs. $\$/\text{kg} \times \dot{m}\ (\text{kg/s}) \times 31.5 \times 10^6\ \text{s/year} \times f_0$
Operating labor		See Table 6.2 in Reference 2
Supervisory labor		10–20% of operating labor
Utilities		See Reference 6
Maintenance and repairs		2–10% of TPI
Variable Cost Subtotal		Sum all direct operating expenses
Fixed cost		
Overhead		50–70% of the sum of operating labor, supervision, and maintenance and repair
Local taxes		1–2% of TPI
Insurance		0.4–1.0% of TPI
Fixed Cost Subtotal		Sum all indirect operating expenses
Annual Capital Charges		Annual payment of interest and principal on loan for total capital $C_{TC}\, i(1+i)^n/[(1+i)^n - 1]$
Annual Operating Cost		Sum of direct costs, IC, and annual capital charge
Product Cost ($/unit production)		Annual operating cost divided by annual production output

which is the same as the FCI determined in Table 12.12. FCI represents money that could not be easily recovered once spent (such as depreciable assets).

Another important quantity is the *capacity factor* f_0 of a facility. Most plants or installed equipment do not operate 24 hours per day or 365 days per year: output may not be required continuously; the facility may close down at night; or equipment may require frequent maintenance and repair. The capacity factor is simply the fraction of time a facility operates on an annual basis. It is important in calculating the total amount of raw materials and utilities consumed and the annual production output of a facility. It does not generally affect other production costs such as labor and capital charges since these must be paid regardless of whether the facility is being operated.

Direct Costs

Variable operating costs include raw materials, by-product credits, operating labor, utilities, maintenance and repairs, and operating supplies. These costs are a function of facility capacity factor, as a change in capacity factor will result in a corresponding change to the variable costs. *Raw materials* are the inputs to the process, such as coal for a power plant or biomass to a biorefinery. Once the cost per unit mass is determined from suppliers, data from the process flow chart can be used to calculate the annual cost of each raw material:

$$\text{Raw material cost} = C_R \times \dot{m}\,(\text{kg/s}) \times 31.5 \times 10^6\,\text{s/year} \times f_0 \tag{12.17}$$

where C_R is the unit cost of raw material (\$/kg) and $\dot{m}$ is the feed rate (kg/s) of raw material into the plant. Note that the raw material cost is proportional to the capacity factor for the plant. Many plants yield by-products during the production of a desired product; for example, char from a fast pyrolysis facility or electricity from a cellulosic ethanol facility. These represent credits in the form of facility income if they can be sold; *by-product cost* is usually enclosed in parentheses and should be subtracted from other costs when annual production cost is summed. Calculation is similar to that employed for raw material cost.

Operating labor represents wages for people who operate equipment in the plant. This quantity can be estimated from tabulations of "Operator Requirements" such as is found in Table 12.15. Obviously, simple equipment or fully automated plants may have little operating labor associated with them on an annual basis (although recall that automated equipment requires the use of an additional cost factor when calculating installed equipment costs. *Supervisory labor* includes managers and clerical staff at the facility; it can be estimated as 10–20% of operating labor.

Utilities represent such process inputs as electricity, potable water, and steam. The cost per unit can be obtained from such references as the Statistical Abstracts of the United States [9] and the Energy Information Administration's Annual Energy

Table 12.15 Operator requirements for various types of process equipment

Generic Equipment Type	Operators per Unit per Shift
Air plants	1
Boilers	1
Cooling towers	1
Water demineralizers	0.5
Electric generating plants	3
Portable electric generating plants	0.5
Mechanical refrigeration units	0.5
Wastewater treatment plants	2
Water treatment plants	2
Conveyors	0.2
Crushers, mills, grinders	0.5–1
Evaporators	0.3
Vaporizers	0.05
Furnaces	0.5
Fans	0.05
Blowers and compressors	0.1–0.2
Gas–solids contacting equipment	0.1–0.3
Heat exchangers	0.1
Mixers	0.3
Reactors	0.5
Clarifiers and thickeners	0.2
Centrifugal separators and filters	0.05–0.2
Bag filters	0.2
Electrostatic precipitators	0.2
Rotary and belt filters	0.1
Plate and frame, shell and leaf filters	1
Expression equipment	0.2
Screens	0.05
Size-enlargement equipment	0.1–0.3

Source: Adapted from Ulrich, G.D. (1984) *A Guide to Chemical Engineering Process Design and Economics*. New York: Wiley.

Outlook. Annual cost for utilities can be calculated in a manner similar to that employed for raw materials and should include capacity factor.

Maintenance and repairs can be expected even for highly reliable equipment and should be included as part of the operating costs. Typically, these will be 2–10% of FCI; the low end representing well-established, relatively simple equipment and processes and the high end for unconventional or speculative processes.

Operating supplies include replaceable materials in a plant not accounted for as part of regular maintenance. They can be estimated as 10–20% of maintenance and repair costs.

Laboratory expenses represent quality control testing or other chemical and physical analyses to support the manufacturing process. These are estimated as 10–20% of operating labor.

Expenses for *patents and royalties* occur when a process is licensed from another organization. This fee is usually fixed in advance, but for estimating purposes can be taken as 3% of the sum of all other direct expenses. In some manufacturing processes, of course, this fee may not apply.

Fixed Costs

Fixed costs include overhead, local taxes, and insurance. Fixed costs are not a function of facility capacity factor and remain the same despite changes in the factor. *Overhead* includes fringe benefits, social security taxes, unemployment insurance, and retirement funds for workers at a facility. It can be a significant fraction of total labor costs and is usually estimated as 50–70% of costs for labor, supervision, and maintenance and repair (which is mostly labor). *Local taxes* are property taxes and can be estimated to be 1–2% of FCI. *Insurance* is 0.4–1% of FCI.

Capital Charges

Typically, a loan of capital (in the form of TPI) must be secured to build and start-up a plant. We shall assume that a loan is secured for the TPI, C_{TPI}, required to build and start-up a facility. The annual interest rate of the loan is i (expressed as a decimal fraction) and the payment period of the loan is n years. To pay off the interest and principle of this loan will require the inclusion of *annual capital charges,* C_{CC}, in the operating costs equal to:

$$C_{\mathrm{CC}} = \frac{C_{\mathrm{TPI}}\, i(1+i)^n}{(1+i)^n - 1} \tag{12.18}$$

The cost of capital can be a significant fraction of the cost of operating a facility. Depending on interest rate (which is a function of both facility risk and the underlying macroeconomic environment) and the number of years of the loan, annual capital charges can run to 5–20% of the TPI and may dominate operating costs.

As an alternative to calculating capital charges, the facility can be considered as an investment by the providers of capital (shareholders), who require a reasonable rate of return on the invested capital. In this case, an *IRR* or *return on investment* (*ROI*) can be set based on those required by investors in similar industries. Most industries acquire financing from a combination of debt and equity; while the actual ratio varies, this can be estimated as an equal split.

Annual Operating Cost and Product Cost

Once direct, indirect, and capital charges are calculated, they can be summed to give the annual operating cost of a plant. The *product cost* per unit of production is simply the annual operating cost divided by the annual production output of the plant. This number can be compared to product cost for competing processes to get an idea whether the facility is worth pursuing, although it is ultimately an incomplete metric for determining the ability of the facility to compete in the larger economy.

12.4 Estimating the Economic Feasibility of Biorenewable Pathways

While capital cost, operating cost, capital charge, and product cost calculations provide a useful reference point for comparing the economics of different facilities employing biorenewable pathways, they suffer from two notable shortcomings. First, none of them provide a means of determining facility *economic feasibility* or its profitability under one or more economic scenarios in which market conditions and commodity prices are accounted for. Second, they are all point estimates, or single data points, and as such cannot account for volatility in market prices (and thus costs), and uncertainty in projections of input costs, output prices, process yields, etc.

The first shortcoming is remedied by employing discounted cash flow rate of return (DCFROR) analysis, which accounts for capital cost, annual operating cost, annual capital charge, annual revenue, and a discount (or interest) rate to calculate one of the three dependent variables: MSP; IRR; or NPV. Each dependent variable has unique advantages and disadvantages as an economic feasibility metric relative to the others. All three, however, account for the major economic forces that directly and indirectly impact facility operations.

The DCFROR for biorenewable facilities is similar to that used to estimate the product cost of biorenewable resources presented above. Instead of seed, fertilizer, and pesticide, however, the DCFROR for biorenewable facilities considers commodities such as biomass, electricity, and/or fossil fuels as inputs. Furthermore, whereas the majority of biorenewable resource operations focus on the production of a single resource, many biorenewable facilities are capable of producing multiple high-value products. In most cases an increase of the yield of one product results in an equal decrease of the yield of a secondary product (e.g., the tradeoff between yields of bio-oil and char). The DCFROR analysis therefore must be able to differentiate between different facility products, reflecting correlations between their respective yields and, when MSP is calculated, capable of accounting for whether a product is a primary product or a byproduct.

12.4.1 Minimum Selling Price

MSP is defined as the lowest product cost capable of yielding an NPV of zero with a predetermined IRR. In addition to direct, indirect, and capital charges, therefore, MSP also accounts for an annual discount rate. Its calculation requires a DCFROR analysis that is capable of accounting for all of these factors over the lifetime of the facility, usually 20 years. It is the simplest of the three primary economic feasibility metrics in that its calculation requires little additional data beyond that required to calculate product cost. While the discount factor can be based on a comprehensive analysis of the economic environment in which the modeled facility operates, it is most commonly set to 10% or a similar number. MSP calculations allow for biorenewable product costs to be compared with the market prices for their non-biorenewable counterparts and some insight into the economic competitiveness of the former to be derived from the comparison. For example, if a 20-year DCFROR of a biomass gasification and Fischer–Tropsch (F–T) synthesis facility calculates an MSP of $3.00/gal for its renewable diesel fuel product, then a favorable comparison with petroleum-based diesel fuel might be made when the market price for the latter is $3.50/gal. Alternatively, investors may decide that it is a poor investment when the market price for diesel fuel is lower than the MSP. MSP calculations are less suitable for biorenewable facilities with a portfolio of products (as opposed to a single product) since they treat the MSP as the dependent variable. While this does not cause significant problems for single-product facilities, its usefulness is constrained when attempting to calculate the MSP of a facility that produces equal volumes of gasoline and diesel fuel, since the MSP can only be calculated for one or the other.

12.4.2 Internal Rate of Return

IRR is defined as the annual compounded rate of return required to make the NPV of all cash flows from an investment equal to zero. It is calculated via Equation 12.13 by solving for i when NPV $= 0$. The key difference between MSP and IRR calculations is that the latter treats the IRR as the dependent variable and uses a market price in place of MSP to determine facility cash flows. For example, the income of the aforementioned biomass gasification and F–T synthesis facility is a function of the market price of diesel fuel rather than the MSP of its renewable diesel fuel product when IRR is calculated. Since the NPV is set to zero, the facility IRR is positive when the market price of the renewable diesel fuel is higher than its product cost. The advantage of the IRR calculation is that by setting the MSP as an independent variable, the market prices of multiple products can be accounted for. Rather than treat the renewable gasoline and diesel fuel products of the fast pyrolysis and hydroprocessing facility in the above example separately, an IRR calculation treats both according to their respective market prices. This permits greater flexibility when modeling pathways with multiple products, as otherwise the products will need to be treated identically for the purposes of calculating MSP.

Accounting for market prices rather than product MSPs is especially useful when modeling facilities with longer lifespans. The twenty-first century has been characterized by high volatility in energy commodity prices, which makes it unlikely that a market price used when quantifying pathway economic feasibility in 1 year will be accurate in following years. Incorporating 20—30-year lifespans into DCFROR analysis makes it possible to account for this volatility, generating a result that is less sensitive to contemporary energy commodity prices. One option is to base the market prices used in the DCFROR analysis on historical prices. For example, a 2008 analysis using the contemporary petroleum price to quantify the economic feasibility of a biofuel pathway would have been making an optimistic assumption since petroleum prices were at historical highs in that year, causing biofuel production to look attractive. The same analysis completed the following year, when petroleum prices fell by half, would have produced a much more conservative result. Basing the market price in the model on the average petroleum price over the previous decade eliminates the sensitivity of the model result to short-term price volatility. Alternatively, several government and private research groups forecast future energy commodity prices on the basis of current and expected market conditions (the Energy Information Administration's online "Annual Energy Outlook" database is one example). While long-term price projections can be very uncertain, they do account for anticipated changes in market conditions and therefore make it less likely that a DCFROR analysis result will be made obsolete by, for example, future increased petroleum demand in China and India or increased natural gas production in the United States.

While IRR as a measure of economic feasibility addresses the shortcomings of MSP, it does suffer from two of its own. First, IRR calculations assume the continuous reinvestment of cash flows in projects with the same rate of return as the IRR. In other words, a 20% IRR result assumes that the cash flows generated by the initial investment are continuously reinvested at a 20% rate of return. This is not always possible in reality as it is unlikely that the original facility will be continuously scaled up on an annual basis using its cash flows from the previous year. IRR calculations therefore have a tendency to overestimate the project's initial rate of return, particularly when an IRR is calculated that exceeds that which can be expected for other investments. Second, IRR represents an expected return on an initial investment and is not suited for comparing possible investments with different capital costs, as the project with the higher capital cost can yield a lower IRR even if its financial return is higher in absolute terms. Based on these two issues, IRR calculations should not be used to compare mutually exclusive investments, particularly when the capital costs are not identical.

12.4.3 Net Present Value

Whereas MSP measures facility economic feasibility on a product-unit basis and IRR measures it on a percentage-return basis, NPV is reported as an absolute value. As such, it avoids several of the shortcomings of the first two and is ideal for comparative analysis of different investments, particularly those with different capital costs. Equation 12.13 is used to calculate NPV, with a predetermined number used for i (as with MSP calculations, 10% is common) and cash flows based on the market value of the facility product(s). A positive NPV represents an investment that adds value in discounted terms, while a negative NPV represents one that reduces value. When comparing the economics of multiple biorenewable facilities, therefore, they can be ranked according to economic feasibility on the basis of their respective NPV values. Unlike MSP, NPV can account for facilities with product portfolios rather than a single product. Unlike IRR, NPV does not overestimate the return for facilities with lower capital costs. Further, it does not automatically make unrealistic assumptions regarding the annual rate of return on cash flows of facilities with high NPVs, as i can be set to a realistic value in this regard. NPV is not as useful as MSP or NPV as an individual benchmark since it does not provide a simple reference point, and many analysts prefer using the first two for reporting the economic feasibility of individual biorenewable investments for this reason. NPV should always be used when multiple mutually exclusive biorenewable investments are being compared, however.

12.4.4 Sensitivity Analysis

When economic feasibility is calculated as a single number, whether MSP, IRR, or NPV, this result is a *point estimate*. In statistics, a point estimate is a "best estimate" of an unknown population parameter. In techno-economic analysis, a point estimate is a single result value for an analysis with a relatively high uncertainty level. Point estimate results can serve as useful benchmarks but should not be relied upon alone since they are very sensitive to the assumptions used to make the calculation.

Sensitivity analysis is an analytical methodology that quantifies and presents the sensitivity of the point estimate result to the TEA parameters. Sensitivity analysis is commonly performed by identifying the parameter value assumptions (the "baseline" scenario) and then creating "pessimistic" and "optimistic" scenarios based on set percentages of the baseline parameter values. For example, if a TEA of a starch ethanol facility employs an ethanol market value of \$2/gal as the assumed (or baseline) parameter value, then the pessimistic and optimistic scenarios would use parameter values of \$1.4/gal (70% of the baseline value) and \$2.6/gal (130% of the baseline value) for the pessimistic and optimistic scenarios, respectively. These calculations are then repeated for all of the parameter assumptions until full pessimistic, baseline, and optimistic parameter values have been developed. Point estimate results are then calculated for each parameter value under the pessimistic and optimistic scenarios (the point estimate result for the baseline scenario does not change since its parameter values do not change), allowing for the sensitivity of the point estimate result to be quantified for each change to the parameter values, both pessimistic and optimistic. Finally, the results of the sensitivity analysis are ranked by identifying the parameters to which the point estimate result is most sensitive. The point estimates calculated for all three scenarios from changes to these parameters are presented by placing these point estimates in a chart in which the *x*-axis represents the point estimate calculation (MSP, IRR, or NPV). These charts are commonly known as "tornado plots" due to the shape that they take when the parameters are ranked vertically from greatest sensitivity to least sensitivity.

Among the parameters to which the result is most commonly reported to be highly sensitive are feedstock cost, process yield, and output market value. The choice of which values to use for these parameters therefore has a strong effect on the point estimate result, and the use of an unrealistic parameter can generate an unrealistic point estimate result. While sensitivity analysis cannot correct this, it does allow readers of the analysis to identify the unrealistic parameter values and roughly determine how replacing them individually with more realistic values affects the TEA result. Ultimately this is of limited use, however, since it does not permit for multiple values to be changed simultaneously.

12.4.5 Uncertainty Analysis

Sensitivity analysis only quantifies the sensitivity of the TEA point estimate result to isolated changes to a single parameter value. Furthermore, only a limited number of scenarios are considered. In reality these changes are not isolated, with two or more parameter values often changing simultaneously, and a very large number of possible scenarios exist. Uncertainty analysis makes it possible to determine the probability that a point estimate result will be achieved based on these different scenarios and changes to parameter values. *Monte Carlo simulation* is a methodology that utilizes repeated random sampling across hundreds or even thousands of trials to calculate numerical results, and it is commonly employed to consider techno-economic analysis under uncertainty. The ability to calculate results for a very large number of trials allows for the calculation of the probabilities that specific numerical value thresholds will be achieved by a TEA model.

The first step of Monte Carlo simulations is the completion of a sensitivity analysis. The sensitivity analysis identifies the model parameter values to which the TEA result is most sensitive, and therefore those that are worth considering further via uncertainty analysis. Monte Carlo simulations are computationally intensive by nature, a requirement that can be mitigated by only considering changes to those parameters that significantly affect the result. The second step is to develop probability distributions for those parameters identified as significant by the sensitivity analysis, for which a number of strategies exist. The simplest is to employ the distribution that is most common to the specific type of parameter. For example, many commodity price distributions over time take the form of a lognormal curve since increased demand and decreased supply in response to falling prices prevent them from ever reaching zero. A drawback of this strategy is that the commonly used distribution is not necessarily the correct distribution for the specific parameter in question. Alternatively, when sufficient data points are available, the data can be fitted to the appropriate distribution curve. This has the advantage of ensuring that the appropriate distributions are used for each parameter, although this will not always be possible when insufficient data are available. Furthermore, cost and price parameters require historical price data for the development of distribution curves, which do not reflect recent structural shifts in the markets considered.

The third step is to identify correlations between the parameters considered by the uncertainty analysis. In many cases, particularly those involving commodities, the market values of two outputs will be closely related, and a move in one will be closely matched by a similar move in the other. For example, some biorenewable pathways produce both gasoline and diesel fuel. Since the fossil versions of both fuels are derived from petroleum, gasoline and diesel fuel prices have historically been closely correlated; it is very rare for a sharp upward movement in the price of one and a sharp downward movement in the other to occur simultaneously. Ignoring such correlations during a Monte Carlo simulation will produce an inaccurate result since it will consider scenarios that are very unlikely to occur in reality. Many simulation software packages include the ability to account for correlations in parameter values during the uncertainty analysis, and this should be done when such correlations are identified.

The final step is to run the simulation based on the probability distributions developed for the considered parameter values. As a general rule, a higher number of trials should be performed during the Monte Carlo simulation when a large number of parameters are being considered and multiple types of probability distributions have been developed. It is not uncommon for TEAs of biorenewable pathways under uncertainty to perform 10 000 or more trials. The result of the Monte Carlo simulation is commonly presented as a probability distribution for the TEA result (i.e., MSP, IRR, or NPV). This can also be presented as a continuous distribution showing the probability that specific TEA result thresholds will be met. Uncertainty analysis via Monte Carlo simulation adds an additional dimension to TEA by calculating the probability that a point estimate result will be achieved. This can have a very significant impact on the results of comparative analyses since the most attractive TEA result among multiple pathways considered may also have the lowest probability of being achieved.

12.4.6 Detailed Example of Estimating Costs for Fast Pyrolysis and Hydroprocessing

As a detailed example of cost estimating, the production of renewable gasoline and diesel fuel via fast pyrolysis and hydroprocessing is presented based on the analysis of Wright et al. [10]. A flow diagram for this biofuel production system is

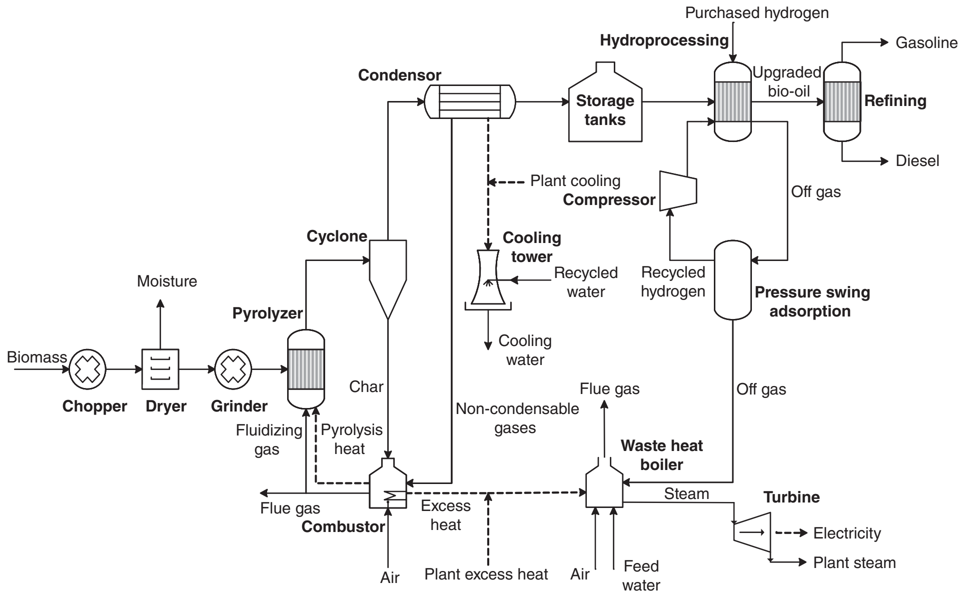

FIG. 12.3 Flow diagram for fast pyrolysis plant. Adapted from Brown, T.R., Thilakaratne, R., Hu, G., and Brown, R.C. (2013) *Fuel*, 106, 463–469.

illustrated in Figure 12.3. Two thousand metric tons per day (MTPD) of biomass feedstock is dried to 7 wt% moisture content and ground to 3-mm diameter size. The feedstock is pyrolyzed at 480°C and atmospheric pressure to yield liquid (bio-oil), solid (char), and gaseous (non-condensable gases or NCG) products. The char is removed via standard cyclones while the vapors are condensed in heat exchangers to yield bio-oil. The char and NCG are sent to a combustor providing process heat for the facility.

The bio-oil is upgraded via hydroprocessing, which consists of a low-severity hydrotreating stage followed by a high-severity hydrocracking stage. Hydrotreating occurs in a hydrogen-rich environment (about 5 wt%) at 7–10 MPa pressure and 300–400°C in the presence of a cobalt–molybdenum catalyst. The hydrotreating step removes impurities and partially deoxygenates the raw bio-oil. The hydrotreated bio-oil then undergoes hydrocracking at 10–14 MPa pressure and 400–450°C in the presence of a nickel–molybdenum catalyst. The hydrocracking step fully deoxygenates the hydrotreated bio-oil and depolymerizes its heavier constituent hydrocarbon compounds to the naphtha and diesel fuel ranges.

Plant capacity is taken to be 134 million liters per year of gasoline and diesel fuel, with equal fractions of both. The first step in estimating cost of production is to

Table 12.16 Purchased equipment costs for biomass fast pyrolysis and hydroprocessing facility example

Item	Equipment Cost C_p[a]
Pretreatment	7 046 210
Pyrolysis and oil recovery	9 744 803
Combustion	16 476 040
Hydroprocessing	16 949 520
Storage	2 027 420
Utilities	3 160 383
TPEC	55 405 410

Source: Adapted from Wright, M.M., Satrio, J.A., and Brown, R.C. (2010) Techno-economic analysis of biomass fast pyrolysis to transportation fuels. *National Renewable Energy Laboratory Technical Report NREL/TP-6A20-46586.*

[a]Adjusted to 2010 dollars.

determine the cost of equipment to be installed in the plant. Wright et al. [10] have determined equipment costs C_p for the proposed facility, which are summarized in Table 12.16 (adjusted to 2010 dollars). TPEC is \$55 400 000, which is only a fraction of the cost of installing the equipment in the facility. The installation cost is calculated from factors for installation, instrumentation and controls, piping, electrical systems, buildings, yard improvements, and service facilities, which are presented in Table 12.12, as previously described. These factors and the resulting installation costs are listed in Table 12.17 for each cost category. The total cost associated with installation is \$111 500 000, bringing the total installed equipment cost to \$167 300 000 (the difference is due to rounding).

These numbers are the basis for preparing a summary of capital costs for the fast pyrolysis and hydroprocessing facility, which is given in Table 12.17. IC (engineering, construction, and legal and contractors' fees) are readily estimated as fractions of TPEC, as described in Table 12.12. The sum of installed equipment and IC comes to \$216 500 000. Contingency is assumed to add 20% to the sum of installed equipment and IC, resulting in an FCI of \$259 900 000. Working capital and land are estimated as costing \$39 000 000 and \$3 300 000, respectively, bringing the TPI to \$302 000 000. In this case the TPI is a factor of 5.46 greater than the TPEC alone.

Sometimes the TPI is divided by the annual capacity of the plant to yield a capital cost per unit output, which in this case is \$2.25 per liter of *annual biofuel capacity*. However, this number can be misleading as it suggests that capital costs are linear with plant capacity, whereas the concept of economies of scale indicates that this capital cost per unit output gets smaller as the facility gets larger. Nor should this number be confused with the production costs per unit of output, which requires a calculation of annual operating costs.

Table 12.17 Summary of capital costs for biomass fast pyrolysis and hydroprocessing facility example[a]

	Cost ($ millions)	Calculation
Equipment Costs		
TPEC	55.4	TPEC × 1
Installation	21.6	TPEC × 0.39
Instrumentation and controls	14.0	TPEC × 0.26
Piping	5.5	TPEC × 0.10
Electrical systems	17.2	TPEC × 0.31
Buildings	16.1	TPEC × 0.29
Yard improvements	6.6	TPEC × 0.12
Service facilities	30.5	TPEC × 0.55
Total installed equipment cost	167.3	TPEC × 3.02
IC		
Engineering	17.7	TPEC × 0.32
Construction	18.8	TPEC × 0.34
Legal and contractors' fees	12.7	TPEC × 0.23
Total IC	49.2	TPEC × 0.89
Contingency	43.3	(TIEC + TIC) × 0.2
FCI	259.9	TIEC + TIC + contingency
Working capital (WC)	39.0	FCI × 0.15
Land	3.3	TPEC × 0.06
TPI	302.2	FCI + WC + land

Source: Adapted from Wright, M.M., Satrio, J.A., and Brown, R.C. (2010) Techno-economic analysis of biomass fast pyrolysis to transportation fuels. *National Renewable Energy Laboratory Technical Report NREL/TP-6A20-46586*.

[a]Hydrogen production scenario.

A summary of operating costs for this fast pyrolysis and hydroprocessing facility is given in Table 12.18. Raw materials include biomass feedstock, catalysts, and process water. Utilities include electricity and solids disposal. Credits are obtained on the fraction of the char not combusted for process heat and the fuel gas produced during hydroprocessing. Other expenses were based on percentages of capital costs and operating labor as detailed in Table 12.14. Total annual operating cost is estimated at $67 280 000 per year, which represents a unit production cost of $0.502 per liter.

An abbreviated version of the facility cash flows is presented in Table 12.19. Note that it only operates at partial capacity in Year 1 due to a 6-month start-up period. Positive taxable income is not achieved until Year 5 due to depreciation and the ability to carry losses (in the form of negative taxable income) forward. The annual present value is calculated as a function of the annual cash income and the appropriate compounded discount factor for the year in question. The cash flow presented in Table 12.19 sets the MSP as the dependent variable; the discount factor (or IRR) is set to 10%. Microsoft Excel's Goal Seek function is

Table 12.18 Summary of operating costs for a biomass fast pyrolysis and hydroprocessing facility[a]

FCI	259.9×10^6	WC	39.0×10^6	TPI	302.0×10^6
Plant capacity factor		Facility capacity (10^6 l/yr)	134×10^6 liters/year		
		Cost ($10^6/yr)	Description		
Variable expenses					
Raw materials					
Feedstock		57.24	$83/metric ton		
Catalyst		1.86			
Process water		0.06			
Raw materials subtotal		59.16			
By-product credits					
Fuel gas		(10.20)	$5/MMBTU		
Char pressure		(1.69)	$22/metric ton		
By-product credits		(11.89)			
Operating labor		1.42			
Supervisory labor		0.44			
Labor subtotal		1.86			
Utilities					
Electricity		6.07	$0.054/kWh		
Solids disposal		1.87	19.8/metric ton		
Utilities subtotal		7.94			
Maintenance		5.20	2% of TPI		
Variable Subtotal		62.27	Sum all variable operating costs		
Fixed expenses					
Overhead		1.11	60% of labor subtotal		
Insurance and taxes		3.90	1.5% of TPI		
Fixed Subtotal		5.01	Sum all fixed operating costs		
Annual Capital Charges		0	100% equity financing		
Annual Operating Cost		67.28	Variable costs + fixed costs + capital charge		
Product Cost ($/L)		0.502	Operating cost divided by facility capacity		

Source: Adapted from Wright, M.M., Satrio, J.A., and Brown, R.C. (2010) Techno-economic analysis of biomass fast pyrolysis to transportation fuels. *National Renewable Energy Laboratory Technical Report NREL/TP-6A20-46586*.

[a]Hydrogen production scenario.

used to determine the MSP that results in an NPV of zero. This yields an MSP of $0.82 per liter.

IRR and NPV can be calculated with the same data by making the MSP an independent variable and using a market price in its place. Note that this will change the "Sales" numbers in Table 12.19 since these are a function of both facility output and output product value. Assuming a fuel market value of $1 per liter and setting IRR as the dependent variable calculates the IRR necessary to achieve an NPV of zero. Goal Seek is used to calculate an IRR under these conditions of 15.4%. Alternatively, setting the IRR to 10% and keeping the same fuel market value yields an NPV of $128 million.

Table 12.19 Summary of cash flows for a fast pyrolysis and hydroprocessing facility[a]

		Year									
Category	Description	1	2	3	4	5	6	7	8	...	20
Sales	Annual sales	95.2	127.0	127.0	127.0	127.0	127.0	127.0	127.0	127.0	127.0
Costs	Annual product cost	69.2	77.3	77.3	77.3	77.3	77.3	77.3	77.3	77.3	77.3
Depreciation	Straight line	74.3	53.0	37.9	27.0	22.5	22.5	22.5	0	0	0
Net revenue	Sales − costs − depreciation	(48.2)	(3.4)	11.8	22.6	27.1	27.1	27.1	49.7	49.7	49.7
Losses forward	Losses (if any) carried forward from previous year for tax purposes	0	(48.2)	(51.6)	(39.8)	(17.1)	0	0	0	0	0
Taxable income	(Net revenue − losses forward)	(48.2)	(51.6)	(39.8)	(17.1)	10.0	27.1	27.1	49.7	49.7	49.7
Income tax	0.39 × taxable income	0	0	0	0	3.9	10.6	10.6	19.4	19.4	19.4
Cash income	Sales − costs − income tax	26.1	49.7	49.7	49.7	45.8	39.1	39.1	30.3	30.3	30.3
Discount factor	10% discount rate	0.91	0.83	0.75	0.68	0.62	0.56	0.51	0.47	...	0.15
Present value	Cash income × compounded discount rate	23.8	41.1	37.3	34.0	28.4	21.9	19.9	14.2	...	4.5

Source: Adapted from Wright, M.M., Satrio, J.A., and Brown, R.C. (2010) Techno-economic analysis of biomass fast pyrolysis to transportation fuels. *National Renewable Energy Laboratory Technical Report NREL/TP-6A20-46586*.

[a]Hydrogen production scenario.

12.5 Costs of Manufacturing Various Biobased Products

12.5.1 Diesel Fuel from Gasification of Lignocellulosic Biomass [11]

The capital and operating costs for gasification and F–T synthesis with coal and natural gas are relatively well known because of significant operating experience with these systems. While lignocellulosic biomass feedstock introduces unique requirements to the pathway, much of the equipment and operating specifications are similar. The capital cost for a new plant ranges between $4.04 and $4.31 per liter of gasoline-equivalent capacity in 2010 dollars. Accordingly, a 2000 MTPD biomass gasification and F–T synthesis facility would cost between $524 million and $637 million. Assuming a cost of $83/metric ton for biomass, the MSP for diesel fuel produced via the pathway is about $1.11–$1.39 per liter in 2010 dollars.

12.5.2 Gasoline from Gasification of Lignocellulosic Biomass [12]

Lignocellulosic biomass can also be gasified to produce gasoline via methanol-to-gasoline (MTG) synthesis, which was commercialized in the 1980s to convert natural gas to gasoline. A 2000 MTPD incurs a capital cost of $210 million in 2010 dollars ($3.81/gal). The MSP for gasoline is $2.05/gal, assuming that the coproduct LPG is sold for $1.61/gal and the feedstock is available at an optimistic price of $59/metric ton.

12.5.3 Ethanol from Lignocellulosic Biomass via Enzymatic Hydrolysis and Fermentation [13]

The cost of producing ethanol from lignocellulosic biomass varies tremendously depending on the feedstock employed, facility capacity, and the choice of pre-treatment and hydrolysis processes. Depending on feedstock pretreatment process, capital costs for a 2000 MTPD enzymatic hydrolysis and fermentation facility are between $380 million and $527 million in 2010 dollars. Production cost estimates vary from $0.95 to $1.27 per liter (assuming a feedstock cost of $83/metric ton). However, the volumetric heating value of ethanol is only 66% that of gasoline. This production cost is equivalent to gasoline selling from $1.43 to $1.91 per liter before tax, transportation, or profit. In contrast, refinery price for gasoline is about $0.80 per liter. Currently, the economics of fermentation is such that the commercial viability of ethanol is entirely dependent on government incentives.

12.5.4 Renewable Diesel and Jet Fuels from Lipids via Hydroprocessing [14]

Capital costs for the production of renewable diesel and jet fuel via lipids hydroprocessing are relatively low, with a 377 MLY facility incurring a cost of $225 million, or $0.60 per liter in unit capital costs. The production cost is between $1.01

and \$1.33 per liter, depending on the facility capacity, the product portfolio, and whether the hydrogen is produced on-site or purchased from an external supplier. Feedstock cost is the major reason for the pathway having relatively high production costs despite lower capital costs; soybean oil feedstock contributes \$0.70 per liter to the biofuel's production cost, for example. Waste fats such as those produced by animal processing facilities are a cheaper feedstock that has been used by some biofuel producers, although its total supply is limited relative to that of lipids from conventional row crops.

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